Public Works Canada
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SOLAR DESIGN COURSE MANUAL

Part II: ADVANCED

November 1982

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This document is not a departmental publication. Do not cite as reference or catalogue in library.

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CHAPTER 1

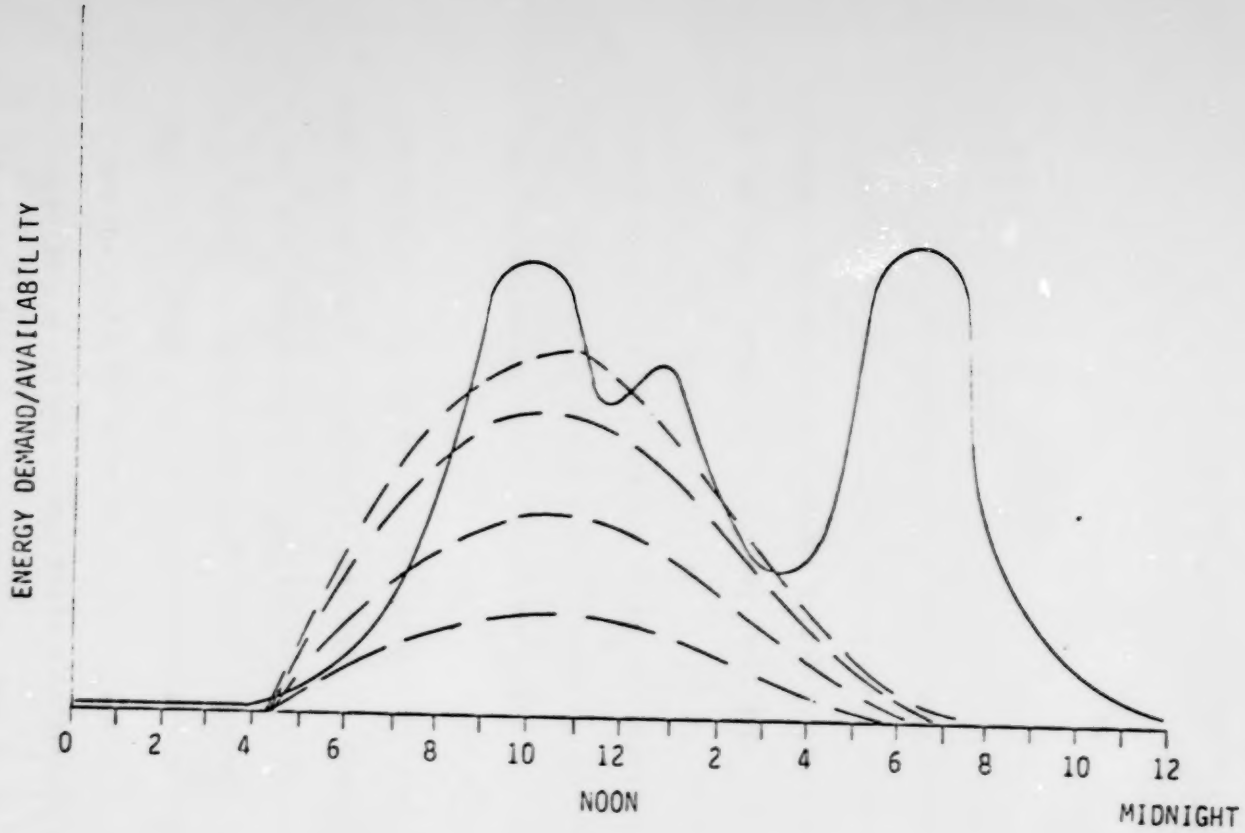
EVALUATING OPPORTUNITIES FOR SOLAR ENERGY SYSTEMS

1.1 OPPORTUNITY IDENTIFICATION

1.1.1 Load Evaluation

When evaluating the opportunities to apply solar energy to meet part of the energy load in a facility, one should look for an application which has a large, continuous, centrally located load which can utilize low temperature energy. At the same time, the impact of energy conservation on the load should be assessed. Energy conservation measures must be performed first to avoid oversizing the solar system. The high fixed costs associated with solar energy systems detract from the economics of small systems. Large loads can justify large solar energy systems, which can benefit from economies of scale.

If there is a continuous demand for solar energy, the problems associated with energy storage are reduced. Thermal storage for more than one day of energy use cannot be economically justified in most applications. A load which is matched to solar radiation availability both on a daily and a seasonal basis will exhibit better economic performance than poorly matched systems. Figure 1.1.1 plots incident radiation against a domestic hot water load profile on a clear summer day for a particular application. Larger collector areas are represented by higher incident radiation curves. At those times when incident radiation exceeds the load,



COINCIDENCE OF DAILY SOLAR AVAILABILITY & DHW LOAD

FIGURE 1.1.1

the difference between the supply and demand curves is available for thermal storage. As one can see, if the designer wishes to meet only a small fraction of the DHW load, as represented by the lower incident radiation curves, little or no storage is required as the energy available never or only rarely exceeds the energy demand. A larger collector array, meeting a larger fraction of the DHW load will, on occasion, receive more energy than can be simultaneously used. The designer must then decide whether the value of energy outside the use curve justifies thermal storage. If not, he must decide whether the increase in system size is justified when compared to the useful energy gained. When thermal storage is used, the FCHART computer program can assist the designer in selecting the optimum collector storage combination. If storage is not used, then the designer must use other tools, such as the WATSUN Interactive program to optimize collector area.

A load may be evaluated by measuring the actual energy use, or it may be estimated using standard engineering procedures, such as those outlined in ASHRAE. Measured data may come in the form of utility bills, or may be obtained by installing specific instrumentation on the facility meeting the load. The load profile often used for DHW load evaluation is the FCHART profile, based on the TRNSYS computer program and shown in Figure 1.1.2., which is the RAND LOAD PROFILE For RESIDENTIAL USE.*

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* Rand Load Profile, ref. Rand Corporation, J.J. Munch, Residential Water, Heating; Fuel Conservation - Economic & Public Policy - R-1498 NSF, May 1974.

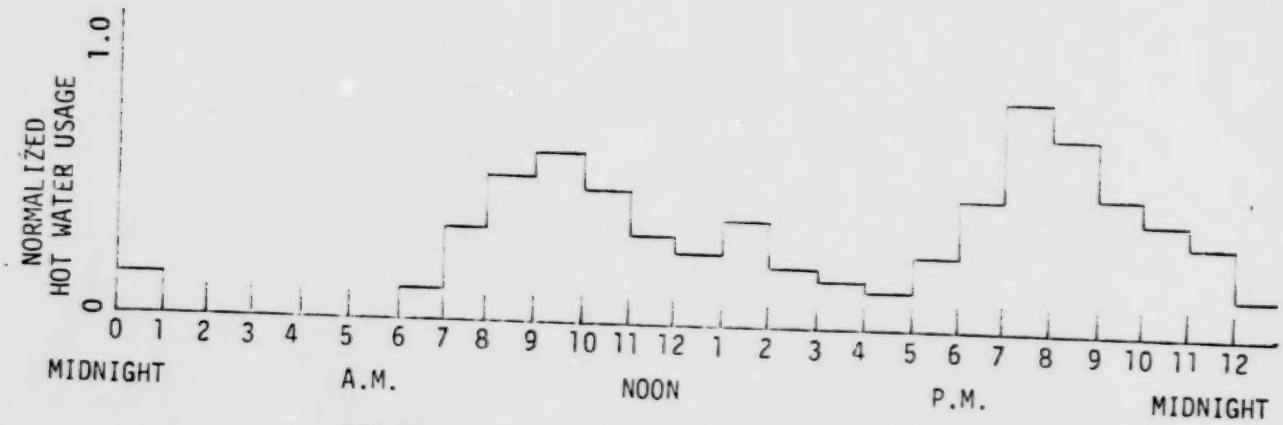

FIGURE 1.1.2 Daily Mass Flowrate Profile

Space heating loads can be evaluated by calculating the heat loss coefficient for the structure and using this coefficient in conjunction with degree day data for the given location or by assuming a furnace efficiency and comparing energy use in the building to historic data to derive a heat loss coefficient. The heat loss coefficient can be used directly in the FCHART 4.0 computer program when predicting the performance of various solar energy system options.

A plot of space heating load versus solar availability would show that peak space heating loads occur at night in small structures while solar radiation occurs during the day. If solar energy is to contribute to the peak heating loads in small structures, thermal storage is required to buffer supply and demand. During spring and fall weather, when heating loads may only occur at night, thermal storage is also required. In large buildings, the time of peak heating loads cannot be generally stated, as building operating procedures and use will determine time of peak space heating loads.

To reduce the cost and complexity of a solar energy system, it is desirable to meet a load at a single, central location. This is generally the case with domestic or process water heating facilities, but space heating applications and ventilation air makeup are frequently located at numerous locations throughout a building, particularly in commercial and industrial installations. The application of solar energy in such instances involves duplication of certain components at each location, which increases overall cost. Such applications may not allow solar energy that cannot be utilized by one system to be utilized by another.

The quality of energy required for a particular application will have a major impact on the economics of the application. Although solar energy systems can provide high temperature energy, there are severe penalties associated with collecting higher temperature energy both in terms of system efficiency and equipment costs. For this reason, applications using low temperature energy are much more favourable than high temperature applications. For example, a space heating system would typically require the solar panels to attain temperatures in excess of 25°C before useful energy is available for contribution to the space heating load. A collector with a performance curve as shown in Figure 1.1.3, a T_i of 22°C (return air from the space being heated) and an outdoor air temperature T_a of -15°C requires an incident insulation rate of 370 W/m² before any useful energy can be extracted from the system. At an incident radiation level of 570 W/m², collector efficiency reaches 30% or could have a useful energy output of 171 W/m², assuming other system losses are negligible. Peak normal radiation levels in Winnipeg and Ottawa are around 710 W/m² in December and 1070 W/m² in January. At the given T_a and T_i, the respective operating efficiencies at these peak radiation levels would be 40% and 54%. However, as collectors are rarely perpendicular to incident radiation and cloud cover frequently reduces radiation levels, it can be seen that a system producing high grade energy will have a low useful energy contribution during those months when heating loads are highest.

If the same collector system were used to preheat ventilation air, its operating efficiency would be much higher, actually equal to the y-axis intercept of the collector performance curve. This occurs because

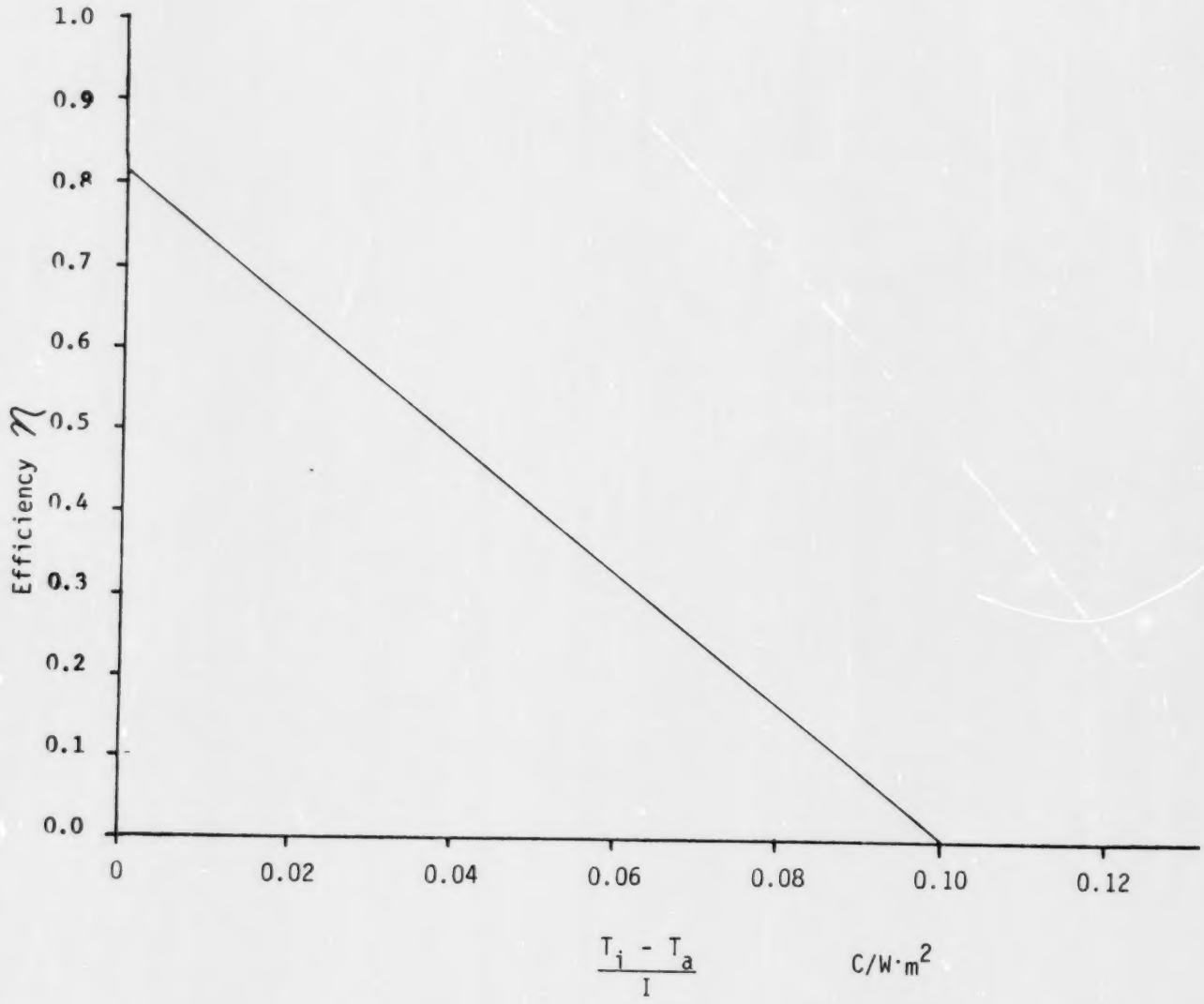

FIGURE 1.1.3

COLLECTOR PERFORMANCE CURVE

the inlet air is outside air, therefore $T_i = T_a$. $\frac{Ti - T_a}{I}$ becomes zero and the collector efficiency becomes the $\tau\alpha$ product. For the preheat application, makeup air would be continuously drawn through the collector whenever there was a preheating requirement, whether or not solar energy is available. When solar energy was incident upon the collector, over 80% of the incident energy would be picked up by the ventilation air passing through the collector. There is no threshold level of incident radiation that must be overcome before the system can contribute useful heat, and the operating efficiency of the preheat system will exceed that of a space heating system under all practical conditions.

The combined effect of lower threshold energy levels and higher operating efficiencies make low temperature applications of solar energy much more favourable than higher grade applications. This is a key factor in identifying solar applications with favourable economic returns. Also using a single solar energy system to meet different levels on a seasonal basis may result in a high annual system performance. For example, air preheating is an ideal winter application for solar energy. Water preheating or swimming pool heating are ideal summer applications, both utilizing low grade energy, relative to ambient air conditions. Occasionally there may be an opportunity to install a single solar energy system to service two loads on a seasonal basis at a cost just slightly greater than servicing either of the loads singly. The result can be a solar energy system with a higher energy performance and cost effectiveness than would otherwise be achieved.

1.1.2 Component Location

The location and orientation of the solar collector array is generally not so critical as one might first imagine. This is important because most systems are designed for existing facilities, and in order to keep costs in line, the solar energy system must frequently utilize building features that are not ideal for solar energy collection. This applies particularly to choosing a location for the solar collector array. In general, it is desirable for a solar collector array to face due south, tilted at an angle equal to the location latitude for a year round application such as domestic water heating, latitude plus 15° for space heating application, and latitude less 15° for summer applications. However, variations in slope and azimuth angles of ±15° from ideals will generally only have a minor impact on system performance, whereas they may result in major reductions in system costs. In fact, variations of collector azimuth of 45° and in some applications 60° from south may only result in reductions of 5% to 10% of annual system performance. This is particularly true of systems designed for summer operation only.

Variations in slope and azimuth may have a positive or negative impact on actual system performance. If morning haze or fog is common, facing the collector array west of south will improve performance. If afternoon smog is typical, an east of south orientation is called for. A flat slope for the collector array will increase the summer solar fraction at the expense of the winter fraction. This may cause overheating in the summer months if summer loads are small.

Shading can significantly reduce the performance of a solar energy system. Aids such as a sunpath diagram (Figure 1.1.4) can be used to show the part of the year and the time of day when an object will obscure direct sunlight on a collector array.

Generally the location of the collector array relative to the other system components is more important than collector orientation. Locating the solar collector array close to the energy user minimizes piping and ducting costs. As ducting and piping constitute a significant fraction of most solar energy projects (10-40%) and are a source of heat loss, their minimization is important. In some instances, it may be possible to use existing mechanical components in the solar energy system. A fan in an existing ventilation system, an existing water line or a second domestic hot water tape can replace necessary solar energy components without adversely affecting the operation of the existing mechanical system.

1.2 OPPORTUNITY OPTIMIZATION

Opportunity optimization involves varying those parameters of a solar energy system which can be manipulated, (eg. collector slope, storage volume, collector type) to find the combination of parameters which will result in the most favourable energy costs over the life of the system. Collector area, for example, is increased to find the point at which the reduction in fixed costs per unit of collector area is less significant than the marginal energy gain attributed to the incremental area. Optimizing collector slope and azimuth can be compared to utilizing existing

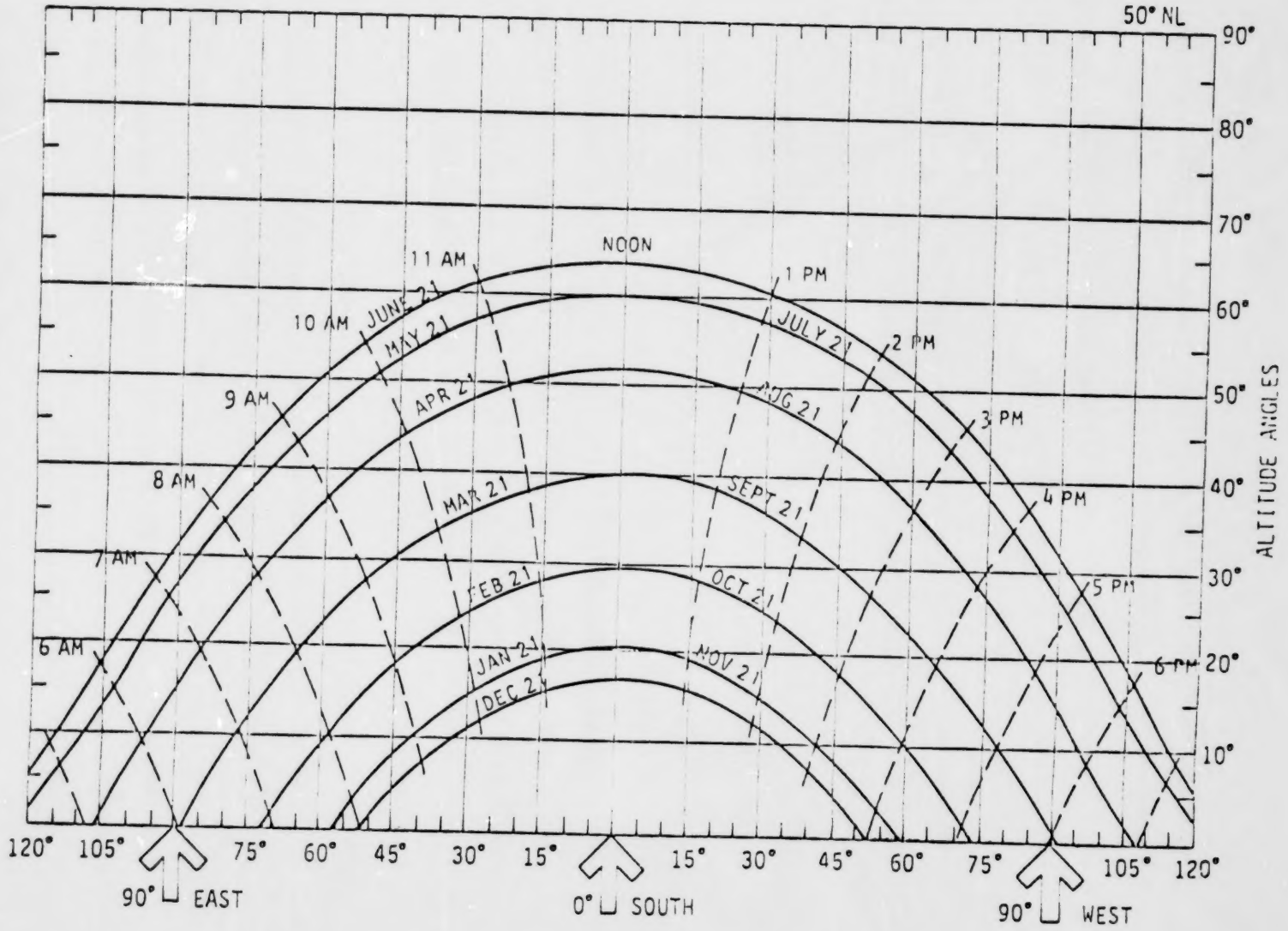

FIGURE 1.1.4

SUN PATH DIAGRAM

building features. The reduced costs associated with collector support structure and mounting may justify the reductions in performance.

The best applications for solar energy are those with a large continuous demand for low grade thermal energy. Low mean collector fluid inlet temperatures result in low heat losses and improved energy collection efficiencies. Low collector inlet temperatures can be maintained if the load being met requires only a small temperature rise, such as the water in an outdoor swimming pool, or if the system is designed to meet a small fraction of a large load, such as pre-heating fresh air makeup in a building ventilation system.

High energy demand allows a system to be sized large enough that fixed and semi-fixed costs can be spread over large collector areas and larger energy contributions, while the fraction of the load met remains low. A low solar fraction combined with a high but fluctuating energy demand may result in a system which utilizes more energy as it is available.

In optimizing system parameters, one should be aware that high quality equipment, with its higher cost, does not necessarily lead to more cost or energy effective solar energy systems. One example of a low cost solar collector possibly out-performing high cost components is an outdoor swimming pool system. The pool temperature is often below the ambient air temperature, due to evaporative cooling of the pool, and to night losses. This means that frequently the solar collector with pool water passing through it will be operating at temperatures below the surrounding air and so rather than suffering heat losses will actually experience heat gains. The more costly, double glazed, well insulated collector will minimize

these heat gains, to the detriment of energy gain. A low cost, uninsulated unglazed collector, will experience significant energy gains from the surrounding air. This is shown in Figure 1.3.1. when T_i exceeds T_a, the collector operate to the left of the vertical axis, and efficiencies actually exceed the ideal collector efficiency. Anytime the $\frac{Ti - Ta}{I}$ variable is to the left of the intersection of the two performance curves, the low cost collector would out-perform the higher cost unit. This occurs for significant periods of time during pool season, thus low cost collectors are favoured for outdoor swimming pool installations.

Among the solar applications that may be considered as amongst the best applications for solar energy are: outdoor swimming pool heating, ventilation air preheating (especially in industrial, laboratory or health care type situations where very large amounts of fresh ventilation air are required to replace contaminated exhaust air), and process water heating (in situations where water consumption is high and the make-up water temperature is low).

1.3 EFFECT OF ENERGY CONSERVATION

When evaluating a solar energy application the designer should also evaluate energy conservation options. In general, energy conservation options are economically more favourable than solar options, and so should be considered before solar energy is evaluated for a particular load.

The implementation of an effective energy conservation measure will reduce the load to be met by other means. The effect of other conservation

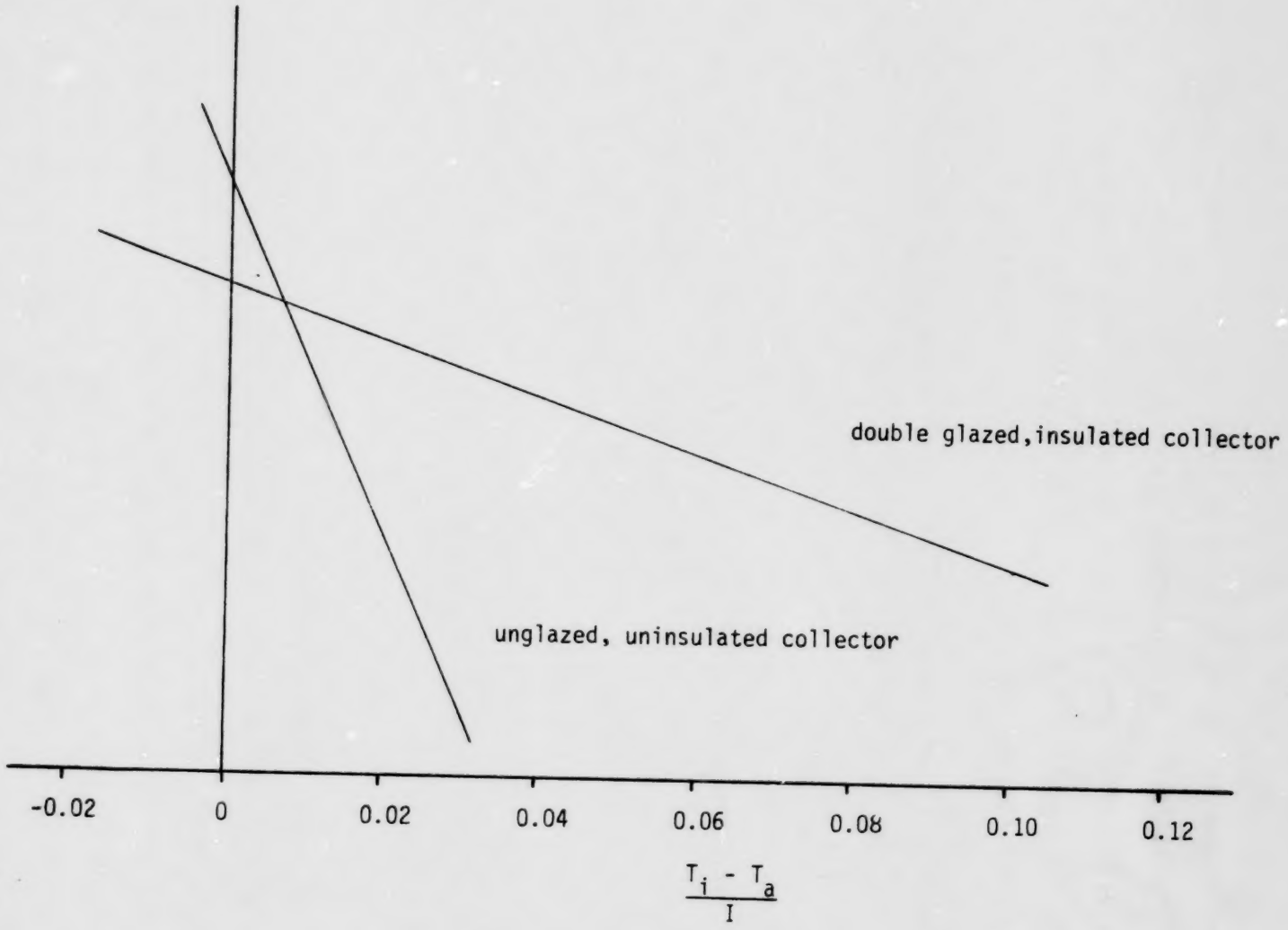

FIGURE 1.3.1

COLLECTOR PERFORMANCE CURVES

measures applied to the same load will therefore be reduced. As the load available to be met by solar energy decreases the energy contribution of the solar energy system will be reduced, thus adversely affecting the economics of the solar energy system.

For example, a DHW system operating with an inlet water temperature of 40°C and a supply temperature of 75°C will have a much higher energy use than the same system with a supply water temperature of 45°C, due to the lower standby losses, and a lower average mixed water temperature. A given solar energy system will contribute less energy to the second system, although it will meet a higher fraction of the DHW energy load. In the first case it may have met 30% of a 100 GJ load while the second case may have met 40% of a 60 GJ load. This reduction in actual energy contribution could mean that the economically optimum system would be reduced somewhat in size, or at least that the economics of the system are less favourable.

1.3.1 PUSH FEASIBILITY REPORT

Before an in-depth evaluation of a solar energy utilization opportunity starts, the facility occupant can complete a Feasibility Report. This report involves selecting a solar energy application and type, quantifying the energy requirements, and then estimating system size, cost and energy contribution using a set of tables and graphs. This report is considered as a preliminary evaluation of the proposed solar energy application. If the proposal is acceptable, the project is funded for a design concept, which is a more comprehensive evaluation.

The Design Concept includes:

- a more complete and detailed description of the load being met by solar energy. Load measurements within a period of time are essential since the solar system greatly depends on the size and profile of the load,
- a proposed system layout, showing the location of major system components,
- a description of the building and any modifications necessary to accommodate the solar energy system,
- a review of energy conservation measures which could be implemented in the facility.

Generally funds are not sufficient for an in-depth energy audit, but the following items should be evaluated:

- resetting DHW temperatures, use of flow restrictors in high use washroom fixtures, and time clocking pumps and exhaust fans where possible.
- a review of assumption and design criteria used in establishing operating procedures.
- a cost estimate, including design, construction supervision, capital costs, expected annual maintenance cost, system energy consumption and any incidental expenditures, such as roof repairs or other building modifications.

The design phase results in a set of structural, mechanical and electrical drawings, specifications and detailed cost and system start up and operational data. Acceptable cost figures based on todays (1982) state of the art, range from 160 $/GJ.a to 350 $/GJ.a.

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CHAPTER 2

2.1 SYSTEM TYPES AND OPERATION

2.1.1 Air Systems

Air collectors have two major applications, space heating and ventilation air preheating. Other applications such as grain drying and DHW heating have also been tried with only modest degrees of success.

In air collectors systems the thermal performance is a function of the collector area. As the collector area increases, the solar fraction will increase as shown in Figure 2.1.1. However, when the utilization per collector unit area is plotted versus the solar fraction a curve such as Figure 2.1.2 results. The curve shows a tendancy towards diminishing returns, as the solar fraction increases the utilization per unit area decreases. It is then desirable to have a low solar fraction in order to achieve a high utilization per unit area so that the thermal performance is maximized.

The solar gain per unit area will vary with the air collector systems application. The highest solar gain per unit area is experienced by the preheating application because the collectors operate at the Y-intercept of Figure 2.1.3. The Y-intercept corresponds to the temperature into the collector being the ambient air temperature. For the space heating application that is not the case and so the solar gain per unit is lower.

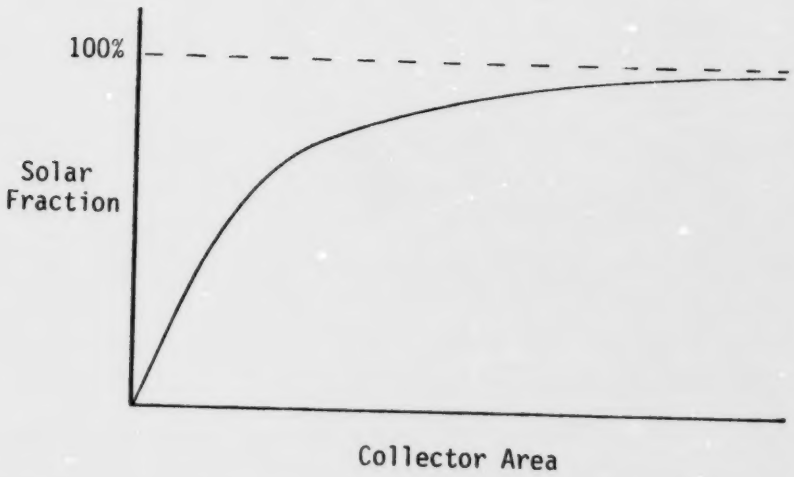


FIGURE 2.1.1 SOLAR FRACTION VS. COLLECTOR AREA

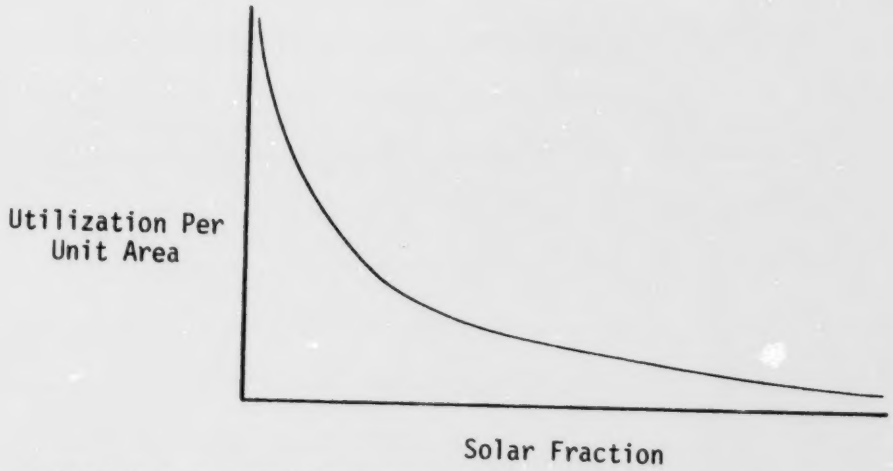
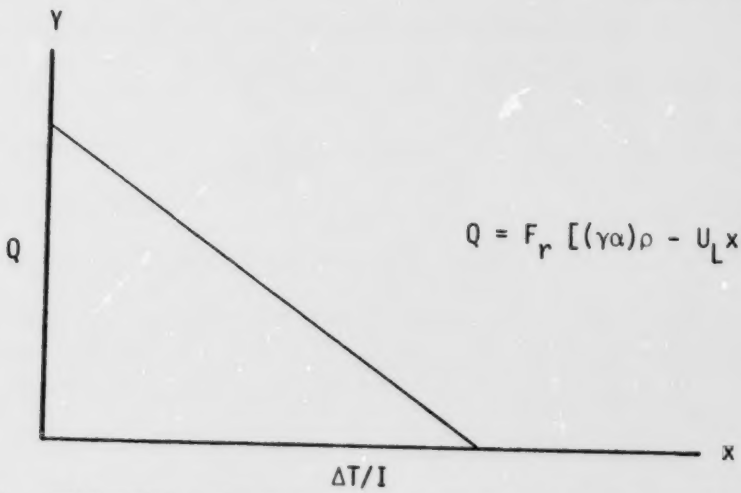


FIGURE 2.1.2 COLLECTOR UTILIZATION PER UNIT AREA VS. SOLAR FRACTION



$$Q = F_r\left[(\gamma\alpha)\rho - U_L x\left(\frac{T_{in}-T_{amb}}{I}\right)\right]$$

FIGURE 2.1.3 COLLECTOR ENERGY GAIN VS. THE INLET TO AMBIENT AIR TEMPERATURE DIFFERENTIAL

The majority of manufacturers recommend a flow rate of 0.01 m^3/s per m^2 of collector area; with one recommendation for the flow rate ranging from 0.01 to 0.03 m^3/s per m^2. The number of collectors that can be safely arranged in series is a function of the pressure drop through the total system. The recommended pressure drop through a collector system should not exceed 0.625 kpa and so the exact number of collectors that can be used is dependent on the manufacturers rated pressure drop.

The pressure drop per collector varies from collector to collector. Currently manufactured collectors have a recommended operating pressure ranging from 0.02 to 0.50 kpa. Collectors operating at the lower pressure make it possible to combine several collectors in series without exceeding the 0.625 kpa pressure drop limit. The collectors having the high operating pressures can not be combined in series without exceeding the pressure drop limit and so a parallel collector array would be required.

The majority of solar systems require more than one solar collector and so several combinations of collectors can be arranged to form a larger collector array. The most straight forward arrangements are series and parallel. At present there are methods for calculating the performance of N collectors in series while using manufacturers data for a single collector.*

In order to maximize the efficiency in a series array of collectors the manufacturers recommended flow rate must be maintained in each

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* Duffie & Beckman - Solar Engineering of Thermal Processes, pp. 268-270.

collector. However when collectors are placed in series the pressure drop of each collector adds together which effectively reduces the airflow rate. And so if N collectors are placed in series then the pressure drop through the collector array will be approximately equal to N times the pressure drop of one collector. Because the pressure drop increases N times the airflow rate must also increase N times in order to maintain the airflow through each collector. The increase in airflow results in the fan horsepower also having to be increased with the increase in fan horsepower being approximately equal to the cube of the number of collectors in series. This results in a larger fan than would be required for a single collector.

This is not the case for parallel collector arrays since the pressure drop per collector does not add together as in a series collector array and so a parallel collector array can employ a smaller fan. However tests by Dunkle and Davey (1970) observed that collectors in parallel experienced variable pressure drops, depending on the collectors location in the parallel array. It was observed that the pressure drop from bottom to top of the collector was greater at the ends of the array than at the center portion of the array. The irregular pressure drops indicate a lack of uniform flow in the collectors and so the performance of collectors in parallel suffers. The reduction of flow results in reduced collector efficiency. The selection between series and parallel collector arrays then becomes a choice of running a larger fan for a series array or running the parallel array system longer to overcome the reduced collector efficiency. Dunkle and Davey recommend connecting the collectors in a series parallel or multiple parallel arrangement which results in more uniform

flow distribution. Other considerations when choosing between parallel and series collectors arrays include manifolding and the collectors design.

2.1.2 Effect of Storage Size on Thermal Performance

When air collectors are used two forms of thermal storage can be employed; sensible and latent heat storage. The storage media choosen is dependent on whether the heat is stored as sensible or latent heat and example being a pebble bed heat exchanger for sensible heat storage. The major characteristics of a thermal energy storage system are (a) its capacity, per unit volume or weight; (b) the temperature range over which it operates; (c) the means of addition or removal of heat and the temperature differences associated therewith; (d) temperature stratification in the storage unit; (e) the power requirements for the addition or removal of heat; (f) the containment associated with the storage system; (g) the means of controlling thermal losses from the storage system; (h) its cost. These characteristics hold true for all the energy storage methods employed in solar energy systems.

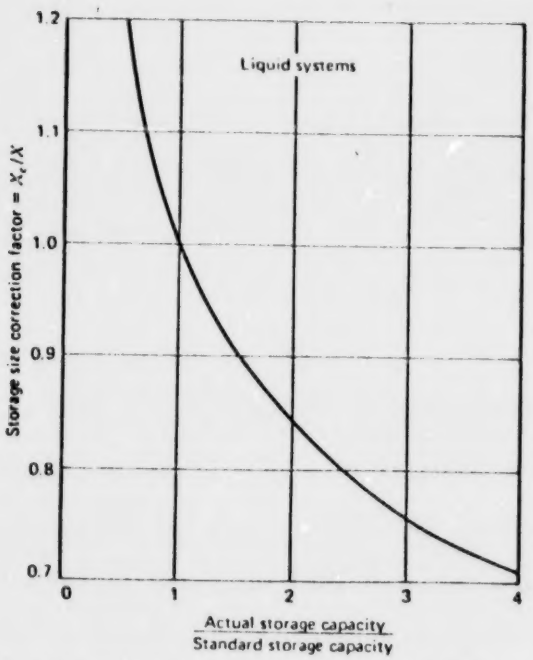
In a packed bed storage a bed of loosely packed particulate material is used to store energy. A variety of solids can be used with rock being the most widely used material. A packed bed storage using rocks will have a high heat transfer coefficient between the air and the solids, which promotes thermal stratification; other advantages of a rock bed storage are the low cost of storage materials and the container; the conductivity of the bed is low when there is no air flow; and the pressure

drop through the bed is low. With these advantages the use of a rock bed storage system is the best suited for an air collector system.

The performance of air systems is less sensitive to storage capacity than that of liquid systems. The storage volume required by an air collector system is dependent on the systems application. Air systems can operate in the collector-load mode, in which the storage unit is bypassed. Pebble bed storage is commonly employed with air collector systems because they are highly stratified and additional capacity is effectively added to the cold end of the bed because it is seldom heated and cooled to the same extent as the hot end.

The storage volume employed by the FCHART computer program for air collector systems is 0.25 cubic meters of pebbles per square meter of collector area, which corresponds to 350 kJ/m²C for typical void fractions and rock properties. The performance of systems with other storage capacities can be determined by employing a storage size correction factor, X_c/X, as indicated in Figure 2.1.4, which was taken from Solar Engineering Of Thermal Processes by John A. Suffie and William A. Beckman

A basic method for determining the spacing between rows of collectors is that the shade angle should not exceed the angle of the sun on December 21 at 12:00 noon. The shade angle is defined as the angle which is formed when a line from the top and the bottom of the southern most row of collectors intersects the bottom of the next row of collectors. If exterior manifolds are used then the top of the exterior manifold becomes the highest point when calculating the distance between collectors using the shade angle. Although this would be ideal spacing between



Storage size correction factor for liquid systems. Standard storage capacity is 75 liters/m^2.

FIGURE 2.1.4

collector rows, other factors must be considered such as the building dimensions, design and orientation. The building dimensions limit the spacing between collector rows, especially when several rows of collectors are employed.

2.1.3 Storage: Advantages and Disadvantages of Rock, Liquid and Phase Change

Good performance of solar heating systems during periods of low or no sunlight is critical if a significant benefit is to be realized. The capability to store substantial amounts of thermal energy for long periods of time is essential.

The two major classes of thermal storage media are those which store heat as sensible heat and those which store heat as latent heat of fusion. Sensible heat is the thermal energy contained by a material, with its heat capacity defined as the quantity of heat which is absorbed or released when the temperature of 453 grams of the material changes 0.555°C.

The latent heat of fusion is the energy that is absorbed when a material melts and released when the material solidifies. The advantage of latent heat storage over sensible heat storage is that a greater quantity of energy can be stored in a smaller volume of material at a convenient operating temperature. Latent heat of fusion materials are commonly referred to as phase change materials or PCMs while the sensible heat media include water and rock.

The most common sensible heat storage media are water and rock but numerous others exist such as water/glycol mixtures, scrap iron and

aluminum, concrete, brick and paraffin oil. Rock is probably the most commonly used storage medium in air systems. A major disadvantage of rock storage as compared to a water storage medium is that rock has approximately one-half the heat storage capacity of water. In order to store an equivalent amount of thermal energy, twice as much rock must be used as compared to water. However, the need for additional storage space is compensated by the elimination of freezing problems, the danger of boiling or the possibility of flooding living space.

The other drawbacks of using a rock storage medium include packing and channeling of the rock, potential for fungi build up if moisture is present in the containment chamber, and leakage of air from the containment. For maximum heat storage capacity the rocks should be of uniform size and distribution.

Water is the other common sensible heat storage medium. Of the liquid sensible heat storage mediums, water has the highest heat capacity while a 30 percent water/70 percent glycol mixture would have a heat capacity approximately 80 percent that of straight water. When a liquid storage medium is used several problems can occur that are not experienced by solid storage media. The most obvious problems unique to liquid storage would be leaks, water seepage, flooding, freezing and boiling. These problems can be reduced with the proper selection of storage tank materials. An example of a liquid storage tank is a reinforced concrete outer shell with a waterproof liner. The waterproof liner would eliminate water seepage and leaks while the outer concrete shell would allow the tank to be used both above and below ground and also provide high load resistance.

The phase change storage materials (PCMs) can be classified into three general groups: a) salt hydrates, b) organics and c) eutectic mixtures.

PCMs offer an attractive alternative to sensible storage media when there is a problem in providing space for thermal storage medium. PCMs require only a fraction of the space needed to store an equivalent amount of thermal energy; an example being that 3.5 m^3 of sodium sulfate decahydrate can store the same amount of energy as does 62.3 m^3 of rock or 28.3 m^3 of water. Despite this significant reduction in storage space, the various disadvantages of PCMs must also be considered.

The advantages of the salt hydrate group are that they tend to be nontoxic, nonflammable, readily available, and inexpensive. However they do not reliably cycle from liquid to solid and some supercool, that is they fail to solidify when the temperature drops below their melting points, and so do not release the latent heat of fusion at the anticipated temperature.

Organics do not have the precipation of solids or supercooling problem, but they do have a relatively high cost and some may be fire or explosive hazards. The organics have a relatively low latent heat of fusion and so require higher volumes than salt hydrates.

2.1.4 Leakage and Thermosyphoning

In all solar collector systems, leakage of either liquid or air can be a problem. Air collector systems experience air leakage at the dampers, along the ducting and even within the collector. For minimum air leakage the ducts should have taped or sealed joints and be made of

fiberglass board insulated sheet metal or flexible insulated duct. A rating of R-4 is recommended as the minimum for duct insulation which corresponds to two and a half centimeters of fiberglass insulation. For ducts, the amount of air leakage is dependent on the length of the ducting, however approximately 5 percent of the air leakage will occur at the inlet and outlet of the ducting.

A second source of air leakage is at dampers. Automatically controlled dampers are employed in air solar systems for controlling the direction of air flow through the rock bed and to the collector and space heating loops. The major problem with dampers in solar air systems is excessive leakage.

The freezing potential for air collector systems with a domestic hot water preheat option is directly affected by the air damper leakage rate. A ten percent leakage in the damper between the heat exchanger and the collector could freeze and rupture the heat exchanger in less than an hour on a cold winter night. In order to minimize leakage, dampers with a leakage rate not exceeding 1/2 percent of the rated flow should be specified.

Air leakage on to the heat exchanger can also be the result of thermosyphoning at night. If air is allowed to leak through the collectors at night when the ambient temperature is below the temperature of the conditioned space, then the collectors will dump heat to the colder environment. This will result in significantly reduced thermal performance. Back draft dampers can be used in the ducts to prevent reverse flow and should be of the flexible flat type or shutter type. They

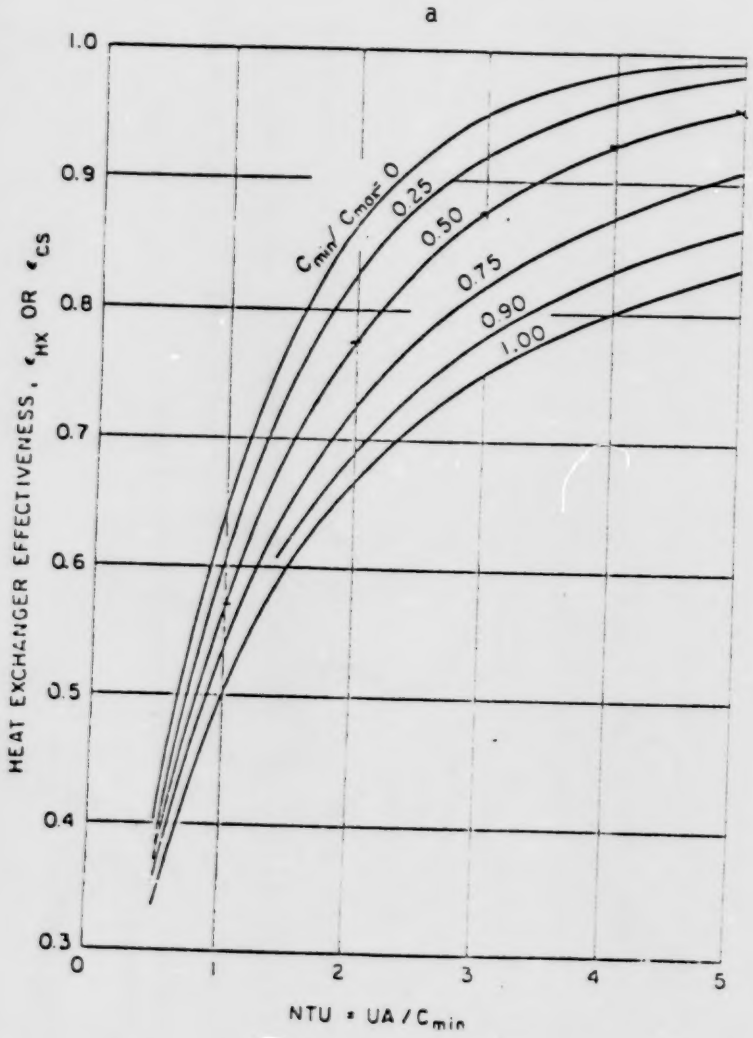
should also be mounted to provide a positive seal against reverse air flow. Reverse thermosyphoning can cause damage to a heat exchanger and also reduce thermal performance but these problems can be reduced with properly installed dampers.

A third source of air leakage is from the collectors. Air leakage from the collectors is dependent on the pressure differential between the collector and the ambient air. A negative collector to ambient air pressure differential will result in infiltration to the collector and so the building becomes pressurized. A positive pressure differential results in the building depressurizing and so air is forced out of the collector. Because of this dependence on pressure differential no typical air leakage rate can be assigned to collectors. Since air leakage reduces an air system's performance, it becomes important to check for air leaks before any insulation or covering is applied to the ducts. This can be done when testing the system by using a smoke pencil to check for leaks.

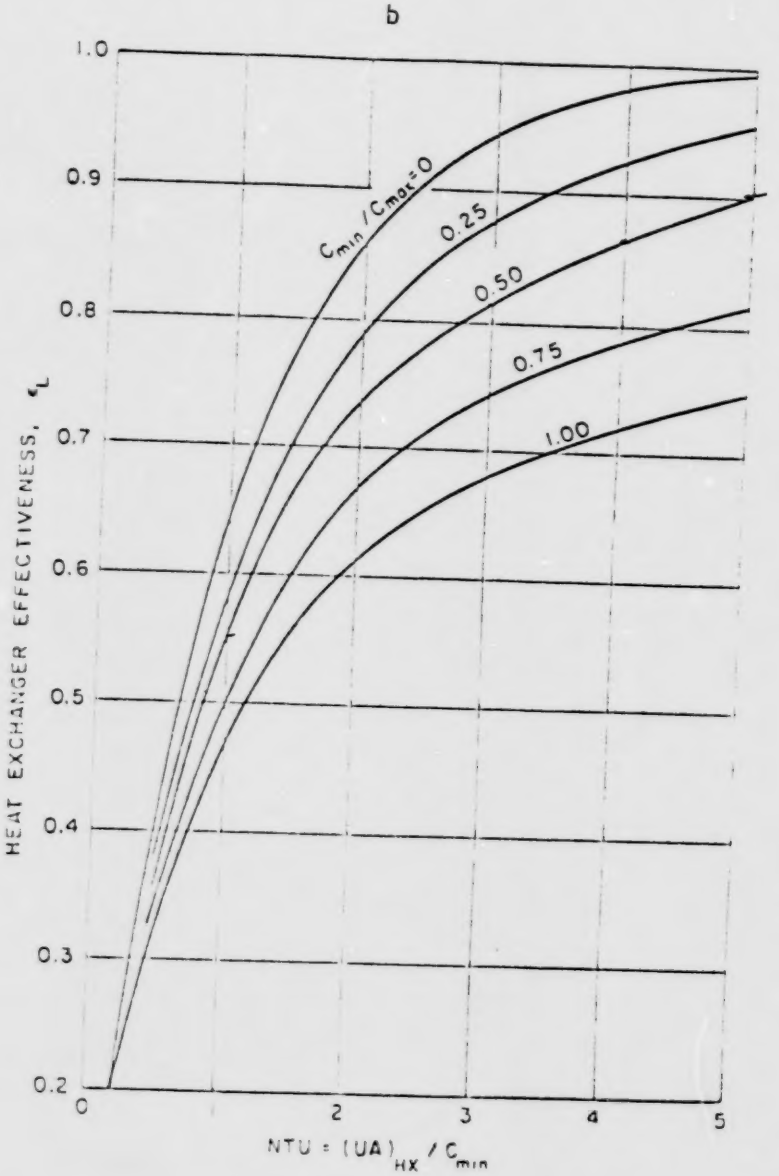
2.1.5 Heat Exchangers

A heat exchanger is used to transfer heat from collector fluid to storage fluid. Perhaps the simplest liquid to liquid heat exchanger is the shell and tube type. For solar systems a counterflow type is appropriate as it minimizes the temperature differences between storage and collector exit fluid temperatures.

A method of sizing heat exchangers which is dependent on the entrance temperatures of the hot and cold fluids, utilizes a factor called heat exchanger effectiveness. Heat exchanger effectiveness is the ratio of



Effectiveness for a Counterflow Single Pass Shell-and-Tube Heat Exchanger



Effectiveness of Cross-Flow Water-to-Air Heat Exchanger

FIGURE 2.1.5

actual rate of heat transfer to a theoretical maximum rate that would occur if the heat exchanger surface area were very large. The heat exchanger effectiveness can also be expressed in terms of the material used in the heat exchanger and the fluid capacitance rates. The effectivenss for a counterflow single pass shell-and-tube heat exchanger is shown in Figure 2.1.5a. The heat exchanger material and the fluid capacitance rate is used to calculate the number of transfer units, NTU, which when plotted against the ratio of minimum over maximum heat-capacity flow rate, can be used to determine the heat exchanger effectiveness. A similar method can be used to determine the heat exchanger effectiveness of a water-to-air heat exchanger. The effectiveness of a cross-flow water-to-air heat exchanger is shown in Figure 2.1.5b. By comparing the two graphs of Figure 2.1.5 an approximate relationship between the effectiveness of a liquid-to-liquid versus a liquid-to-air heat exchanger can be made. All of the ratios of the minimum over maximum heat capacity flow rate, except for the 0, resulted in a higher heat exchanger effectiveness for the shell-and-tube heat exchanger, for all the number of transfer unit values. From the graphs it appears that the largest difference in heat exchanger effectiv-ness occurred at 5 NTU's and at the 1.0 curve C min/C max, where C is the heat capacity flow rate (i.e. mass flow rate of the fluid multiplied by specific heat of the fluid). Heat exchanger effectiveness is the ratio of actual rate of heat transfer to a theortical maximum rate that would occur if the heat exchanger surface area were very large (infinite). At that point the liquid-to-air cross flow heat exchang-er had an approximate heat exchanger effectiveness of 0.74 while the

liquid-to-liquid heat exchanger effectivenss was 0.83. From the curves for these two specific types of heat exchangers the liquid-to-liquid heat exchanger consistantly obtains a higher heat exchanger effectiveness. There are however other configurations of heat exchangers but the liquid-to-liquid types should experience higher effectivness than comparable liquid-toair heat exchangers.

The cost disadvantages of custom made equipment as opposed to off-the-shelf equipment can be large. When custom made equipment is used both the design and manufacturing process cost will increase several times. Since custom made equipment implies a one of a kind system, no assumptions common to solar systems can be employed by the design engineer and so additional engineering design time will be required. The assembly of custom made collectors by manufacturers would be several times the cost of the more cost effective mass produced collectors. The same would be true of the solar system components and so the equipment cost could be several times higher than the mass produced off-the-shelf equipment. The higher cost disadvantage of custom made equipment limits its application to very few systems and so custom made equipment should not be considered except for extreme circumstances.

2.2 LIQUID SYSTEMS

2.2.1 Introduction

The principal applications of liquid cooled collectors are for air preheating (or heating) and water preheating (or heating). Preheating

applications will result in higher collector operating efficiencies than when solar energy is employed for heating to final conditions, in a given situation.

The simplest system type is the thermosiphon, in which solar collectors are located below the thermal storage. Natural convection circulates the solar fluid from storage through the collectors when the collector temperature is above that of the thermal storage. Thermosiphons require no circulation pumps or controls. The physical position of the components in thermosiphon systems is critical for satisfactory system operation.

Due to physical constraints on the location of components in most liquid systems, pumps are usually used to induce fluid flow through the solar energy collection system rather than relying on free convection. Controls are required to coordinate pump operation with energy availability.

When thermal storage is used it is usually water. Systems in which this water is circulated through the solar collectors are called direct heating systems. In all Canadian locations, some form of freeze protection is required for liquid collectors which operate year round. For direct water heating systems this may be achieved by automatically draining the water from the solar collectors anytime there is a risk of freezing. In space heating applications, an antifreeze solution may be used as a solar fluid and for thermal storage. Indirect or dual fluid systems circulate an antifreeze solution through the solar collectors and use a

heat exchanger to transfer the energy collected to water for storage or use.

Although liquid cooled collectors may be used for space heating applications, the high operating temperatures required for most space heating applications degrade system performance. The high cost of interfacing a solar space heating system with the conventional system further detracts from its feasibility. Air systems tend to be similar and less expensive than liquid systems for air preheating applications.

The most common uses for liquid collectors are swimming pool process or domestic water heating and preheating. The advantage to these applications is that the load commonly occurs when solar energy is available and in many instances any energy available in excess of 10°C is useful. Space heating requires 20°C or higher collector fluid temperatures. The technical complexity of systems varies greatly. In general, the cost of energy collected can be reduced by keeping the system simple and designing it to meet a small fraction of a large continuous load.

2.2.2 Effect of Heat Exchangers on Performance

A heat exchanger is required to transfer energy between the two fluids in indirect (dual fluid) systems. If the fluid to be heated is water, then the water is normally used as the energy storage medium. In this case the heat exchanger will be in the collector loop, as shown in Figure 2.1.6.

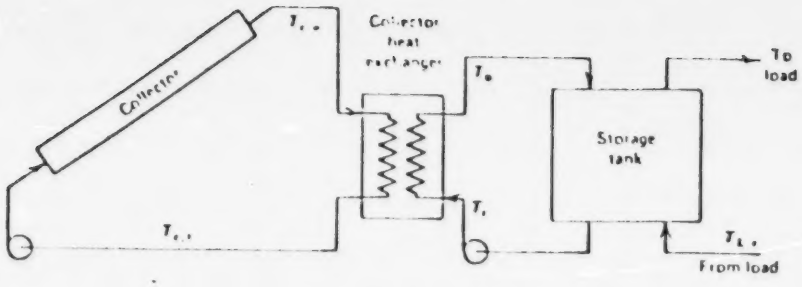


FIGURE 2.1.6

HEAT EXCHANGER IN COLLECTOR LOOP

The transfer of heat between the two fluids requires a temperature difference and thus results in a loss of available energy. For a given storage tank temperature, the inlet temperature to the collector will be higher and its efficiency lower. This effect can be accounted for by correcting the value of the collector heat removal factor for the collector (F_R), to a new value given by

$$F_{R(new)} = \frac{F_R}{1 + \left(\frac{A_c F_R U_L}{(\dot{m}Cp)_c}\right)\left(\frac{(\dot{m}Cp)_c}{\varepsilon(\dot{m}Cp)_{min}} - 1\right)}$$

where A_c = collector area

U_L = collector loss coefficient

$\dot{m}$ = mass flow rate

C_p = specific heat

ε = heat exchanger effectiveness

subscript c = for the collector fluid

subscript min = the lower of the values for the two fluids passing through the heat exchanger.

The heat exchanger effectiveness is defined by

$$\varepsilon = \frac{Q}{(\dot{m}Cp)_{min} \times (T_h - T_c)}$$

where Q = the heat transfer rate

T_h = entering temperature of the hot fluid

T_c = entering temperature of cold fluid

Figure 2.1.7 shows the magnitude of this effect. For a typical collector with $(\dot{m}C_p)_c = (\dot{m}C_p)_{min} = 160$ W/°C

$F_R U_L = 4 W/m^2$ °C

and $A = 2m^2$

a heat exchanger effectiveness of $\varepsilon = 0.6$ will result in a decrease in performance of only 3%. This effectiveness is easy to obtain in a counter-flow heat exchanger. In a crossflow or concurrent heat exchanger, more surface area will be required, and in a free convective heat exchanger, such as the jacketed tank type, the effectiveness will be much lower and the impact on system performance will be considerable.

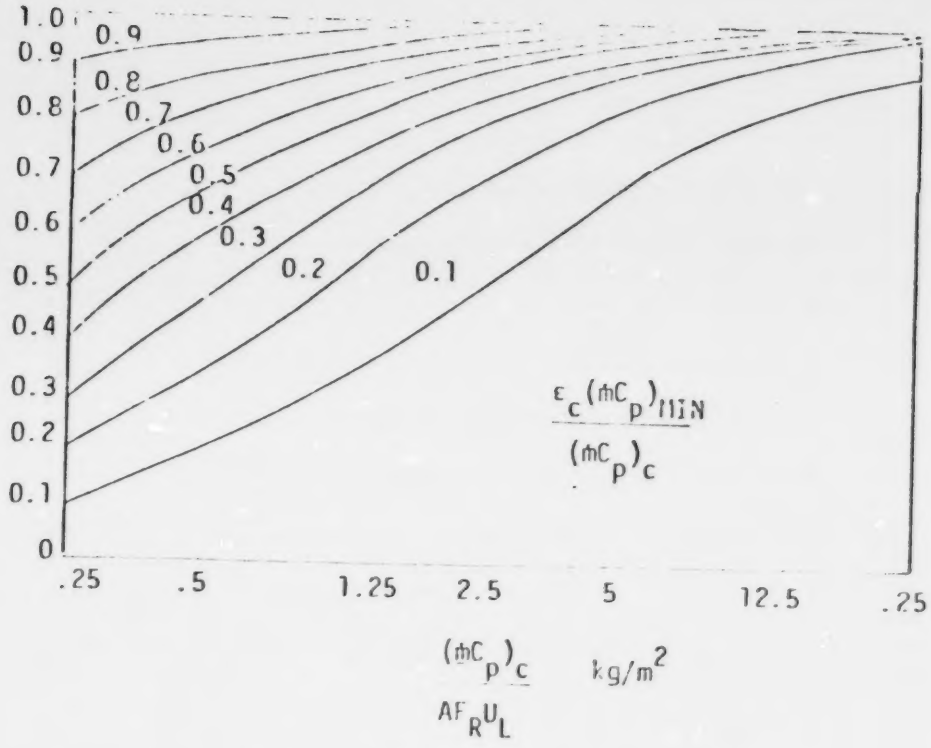


FIGURE 2.1.7 COLLECTOR HEAT EXCHANGER CORRECTION FACTOR

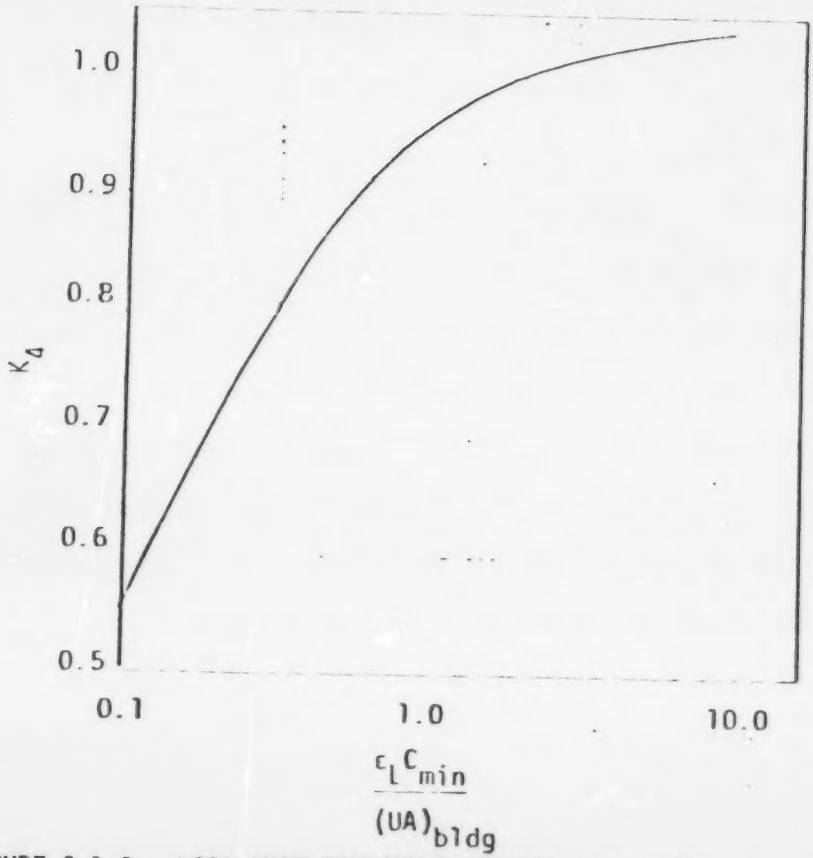


FIGURE 2.1.8 LOAD HEAT EXCHANGER FACTOR, K_4

If a liquid cooled collector is used for space heating, the storage will often be in a liquid and there will be a heat exchanger between the storage and the load. This heat exchanger will also result in a decrease in system performance. A designer who is taking a sophisticated approach to the optimization of such a system will probably use hour by hour simulation to analyse the effect of the performance of this heat exchanger on the systems performance. A simpler approach, taken from FCHART, can provide the designer with an estimate of the impact of the load heat exchanger. The y-intercept, $F_R(\alpha\tau)$ of the collector efficiency curve is multiplied by a correction factor defined by

$$K_4 = .39 + .64 \exp. \left(\frac{-.139\ (UA)_{bldg}}{\varepsilon\ (\dot{m}Cp)_{min}} \right)$$

where $(UA)_{bldg.}$ = the thermal conductance of the building and the other variables are defined as above.

Figure 2.1.8 presents this correction factor graphically. This correction is valid in the range $.5 < \frac{\varepsilon(mCp)_{min}}{(UA)_{bldg.}} < 10$

2.2.3 Losses From Liquid Cooled Solar Energy Systems

The two main types of solar energy system losses are heat losses from lines, tanks heat exchanger, etc., and parasitic energy consumption. The latter term refers to energy consumed by the system to make it operate, such as pumping power and power to operate control systems.

It is difficult to generalize about the significance of either of these parameters. The amounts vary widely from one design to another. The

best way for the design engineer to develop a feel for the significance of these numbers is to calculate them for each system he designs.

A review of several service water heating systems indicates that the parasitic power can vary from about 2% of the useful energy collected for large well designed systems to close to 10% for some smaller systems. Heat losses from the system also vary considerably, with a typical figure for a well designed system being about 10%.

The job of optimising the insulation thickness is a straightforward one which the mechanical design engineer faces repeatedly. In the design of a solar energy system the task is easier than normal because there is no need to speculate on future fuel prices or interest rates, it must be decided whether spending another $1,000 on solar collectors will gain more energy than spending another $1,000 on insulation will save.

As the percentages listed above indicate, parasitic power and heat losses are by no means negligible in a solar energy system, and the careful designer should be sure that he does not allow either of them to become excessive.

2.2.4 Methods of Operating the Solar Energy Storage Tank

The design and operation of the storage system has a major influence on the thermal performance of a solar heating system. The temperature of the liquid leaving the storage system controls that of the collector coolant leaving the heat exchanger and entering the collector and so controls the collector efficiency. Thus the lowest possible temperature

at the outlet of the storage tank will result in the best possible system performance.

For a given load and a given solar energy system, the lowest storage tank outlet temperature occurs when the liquid in the tank is kept stratified. This should be a major objective of the system designer. The thermodynamic significance of tank stratification, and ways to achieve it in practice are discussed further in Chapter 3.

One of the problems which designers face is choosing the proper tank size. In a space heating system the issue is a simple one, because the storage tank fluid recirculates, so that all the heat stored above the storage temperature can be used, while none stored below is used. Thus the larger the tank the more usable energy it can store, and the sizing of the tank is an economic optimization problem.

In a service water heating system the problem is different. The designer must decide whether it is better to maintain storage at a temperature higher than the set point and temper the water to the required temperature, or to size the tank large enough that the temperature never approaches the set temperature. There is little published information on this topic, but one study* led to the conclusion that the storage tanks should hold about one day's water requirement.

It is not difficult to see why there should be a thermodynamic optimum size for the storage tank in a solar domestic hot water system.

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* G.K. Yuill and B.C. Bradley, "The Modelling of a Solar Domestic Water Heating System" System Simulation and Economic Analysis for Solar Heating and Cooling Conference, San Diego, 1978.

Energy can be extracted from the tank only by using water. Thus, if 400 L of water at 60°C is required, and the make up water temperature is 10°C, a tank containing 400 L of water at 60°C can supply the entire load. A tank containing 5000 L of water at 50°C contains 10 times as much energy (measured above the inlet water temperature) but it can supply only 80% as much as the smaller tank when the 400 L is drawn out. Thus it is better to use the smaller tank and allow it to exceed the set point temperature of the load on bright summer days, rather than to use a very large tank.

If this approach is taken, the tank temperature will occasionally rise to well above the set temperature of the service hot water system. This creates several problems. One is that the low efficiency of the collectors at the higher inlet temperature may reduce the energy gain to less than the parasitic energy consumption and the line losses in the primary loop. A second is that the high temperature may endanger users of the water. Finally, the higher temperature may damage system components or cause a pressure increase in the system.

The first problem is not a serious one. Most control systems are set to shut off at a slight positive temperature difference, so that parasitic power will not be wasted. Since parasitic power is independent of temperature, the same control setting will be adequate at all temperatures.

One possible operating mode for a solar energy system will run the system even when it is losing energy. Primary loop coolant leaves the heat exchanger at some temperature T_o, and loses heat in the collector supply line. It gains heat in the collectors to rise to a temperature just

above T_o. It then loses more heat in the collector return line to return to the heat exchanger at a temperature less than T_c. Thus the primary loop coolant cools the storage tank water instead of heating it in the heat exchanger, but the circulating pumps continue to run because the collector outlet is hotter than the storage tank. This problem can be eliminated by raising the temperature difference required to keep the pumps operating, or by increasing the insulation level on the primary circulation lines. The problem is not increased by using a smaller, hotter tank, since for every tank temperature in any given system there will be a narrow range of insolations which can cause the system to operate in this way, if the turn-off temperature difference is set too low. This narrow range of insolations will occur at least once every day the system operates.

The second problem with the use of small, higher temperature tanks is the risk of scalding. This can occur if the tempering valve is not fast acting enough, for example. When no water is being used and the temperature valve is in the "full hot" position. If a tap is turned on, hot water will move down the line and some will pass through the tempering valve before it has time to react. This could result in injury to the water user.

Scalding by water from domestic hot water systems is a significant cause of injury in Canada. About 300 young children, and a large number of adults, receive medical treatment for third degree burns received in this way every year. Of the children, about 100 require hospitalization. In a U.S. study it was found that one third of the children admitted to hospital for tap water burns died of their injuries.

Figure 2.1.9 shows the time taken to cause third degree burns in an adult, as a function of water temperature. Children are burned more quickly. It is obvious that water in the temperature range which might frequently be reached in a solar energy system, and which might be no problem from the materials point of view, can be highly hazardous to the user. This is particularly true because of the variation in the temperature of solar heated water. (Most scalds to able-bodied adults occur when they are travelling.)

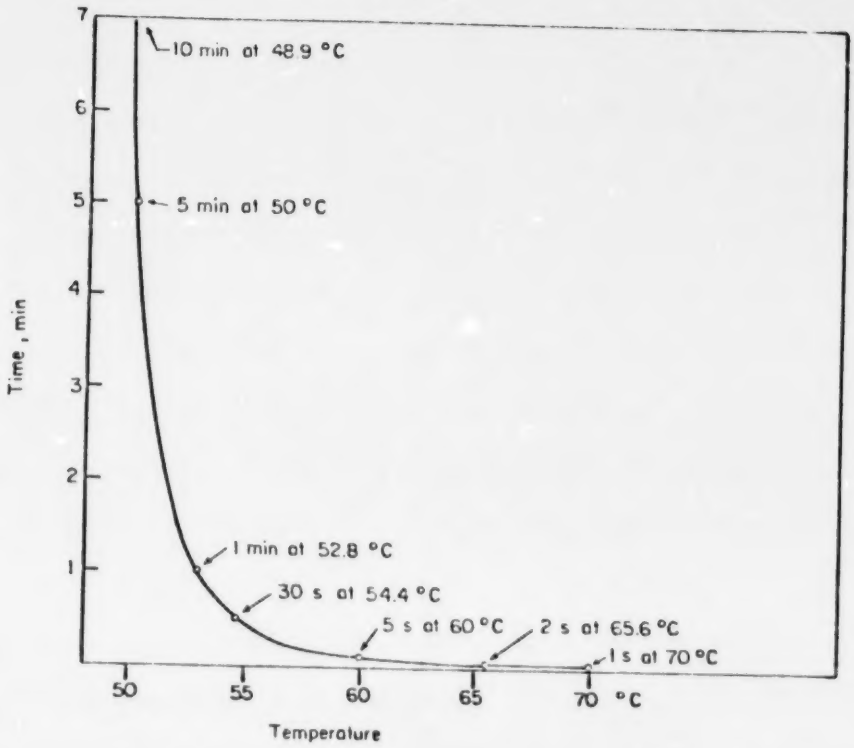


FIGURE 2.1.9

EXPOSURE TIME AND WATER TEMPERATURE
TO CAUSE THIRD DEGREE BURNS

Some plumbing codes require that there must be a storage tank between a tempering valve and the point of use, to eliminate the possibility of short term temperture transients. This requirement can be met and water users can be protected by installing the tempering valve between the tanks of a two tank system. This approach decreases the energy storage capacity of the auxiliary tank, but this is not likely to be a problem when solar energy input is so high that the tempering valve comes into use. In this arrangement the auxiliary heat source may be used to make up auxiliary tank loss even when solar energy is available and not utilized. However, to avoid this it would be necessary to set the tempering valve temperature above the thermostat setting on the auxiliary tank. This would reintroduce the risk of scalding due to unexpected water temperature changes.

The third problem, that of damage to the system by excessively high temperatures, has several possible solutions. One is to design the system to have sufficient heat loss that it never exceeds the safe temperature limit even under no-load conditions. This approach results in excessive losses under other operating conditions.

A second solution is to shut down the circulating pump when the storage tank reaches the temperature limit, and allow the collectors to stagnate. This approach has two disadvantages. One is that glycol solutions degrade faster at high temperatures. The other is that, although collectors should be designed to endure their stagnation temperatures, material degradation will be faster and the lifetime of the unit will be shorter if it stagnates frequently. In drainback and draindown systems,

this technique is more feasible, since the glycol degradation problem does not exist.

A liquid-to-air heat exchanger can be used to dump heat from a solar energy system to limit its temperature. It must be installed outdoors since extra heat is definitely not required indoors during the part of the year when the solar energy system will overheat. A good location is on the collector return line, as a parallel branch, isolated by two three-way valves. When the limiting temperature is exceeded, the valves open and the heat exchanger fan is turned on.

The heat exchanger, with a fan, two valves and the associated controls is a very expensive way to dispose of excess heat for a few hours a year. (If the system overheats for more than a few hours then the system is too large relative to the load.) A cheaper approach is to dump water from the storage tank through a thermostatic temperature relief valve. This is a resetting valve, which closes when the temperature of the stored water drops back below the set temperature. An ordinary temperature relief valve, which trips and stays open when the set temperature is exceeded, can not be used for this purpose.

This method of limiting the system temperature wastes water, but the cost will usually be insignificant compared to the capital cost of a cooling coil. The main application of this approach is to provide protection against unexpected overheating due to unexpected loss of load. By definition, this will seldom occur. Expected overheating should be dealt with by decreasing the size of the collector array relative to the load.

The final decision, on whether a cooling coil or the use of mains water is cheapest, must be made by the designer for the specific application. In general the use of mains water will turn out to be the more economical solution to the problem of disposing of surplus heat.

2.2.5 Collector Coupling Devices For Liquid Systems

The pipe connection to the solar collector is a critical area of concern. Fluid leakage at the collector couplings can result due to pipe expansion and contraction, galvanic corrosion and poor workmanship.

When several collectors are employed in a long array the expansion and contraction of the pipe can result in over 3.0 mm of travel for a 3.0 m length of supply and return headers. To accommodate this travel, the piping must be allowed to change in length relative to the panels to which it is connected. In order to minimize the stresses on the collector couplings the connections between the panels and the headers must allow for motion. Three methods are shown in Figure 2.1.10 which allow for external header motion.

Item A shows a steel nipple which is welded to the header with a coupling on a short nipple screwed into the panel. The bend in the nipple assists in absorbing expansion. When up to four collectors are employed the nipple should be approximately 20 cm in length. If larger collector assemblies are used then the nipple length should follow standard piping practice.

Item B shows flare type steel fittings for making the connections to both the collector and the header. An "S" bend, not shown, is desirable

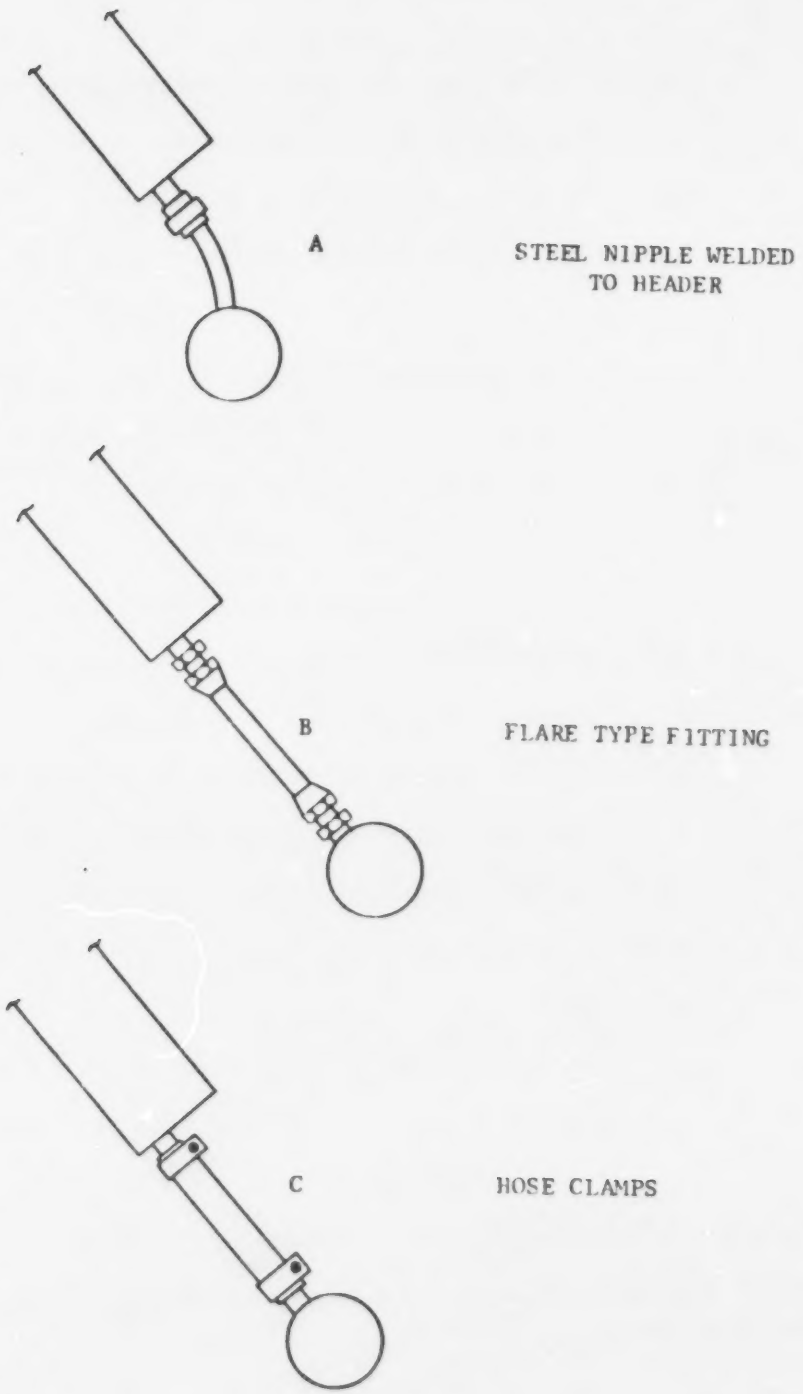


Figure 2.1.10
Flexible Manifold Connections

to allow for expansion and dimensional differences between the header and adjacent collectors.

The third method shown in Item C is the use of an elastomeric hose. Two concerns with respect to hose material are the durability when exposed to sunlight for long period of time and the permanency of clamping. Many hose materials are available but the material selected should be compatible with the fluid used. Silicon based hoses are commonly used as they are compatible with the majority of solar system heat transfer liquids which are combinations of ethylene, glycol and water.

Several types of hose clamps are used with elastomeric hoses. The most common clamp types are the screw, crimp and spring clamp. The screw clamp can slice a hose when overtightened but this can be prevented if a smooth liner is used. The hose may "set" over time and so the clamp will have to be checked to insure clamp tightness. Spring clamps have been successful in avoiding hose damage and in automatically compensating for hose "setting". In general a spring clamp has less clamping force than a screw clamp and there have been cases in which expansion cycling has gradually worked the hose loose. If a shoulder is included on the end of the pipe connection then the spring clamp can prevent this problem from occurring. A crimp clamp is another option, which has not often been used.

The other methods for providing expansion/contraction protection are by using victaulic couplers and expansion bellows. Both of these devices are better suited for use with internal manifolds and for interconnecting panels in vertical arrays and not as direct connections to the collectors. By including these expansion/contraction protective devices on

either interior or exterior manifolds the stresses due to expansion/contraction will be reduced and the potential for leakage at the collector couplings is minimized.

A second source of liquid leakage will occur due to corrosion in the pipe system. Galvanic corrosion will occur at couplers if dissimiliar metals are used. As a general rule, the use of dissimiliar metals should be avoided in a hydronic system. If this rule is not followed and appropriate preventive measures not taken, then galvanic corrosion can reduce the lifetime of the solar system.

Several measures can be employed which will prevent galvanic corrosion.

1. Ideally, the same metal should be used throughout the system. Wherever possible, combinations of metals which are close together in the electromotive series should be selected.

2. If dissimiliar metals have to be used then the area of the less noble metal should be relatively large compared to the area of the more noble metal. For example, a small area of steel should be coupled with a large area of aluminum.

3. Galvanic corrosion can be reduced or prevented by slowing the flow of electric current between the two metals by installing electric insulating materials between the two metals.

4. A protective coating such as paint should be applied to the more noble and more corrision-resistent metal.

5. Add chemical inhibitors to the electrolyte. Inhibitors can be classified as either anodic or cathodic depending on what metal is to be protected.

These measures can be taken either separately or in combination.

The last significant cause of leakage at collector couplings is due to poor workmanship. This is a particular concern for soldered

connections. To ensure complete penetration of solder into a pipe connection, both the inside of the connector and the outside of the tube should be soldered separately. The connector and tube can then be joined together while the solder is sufficiently soft. By reheating the joint a tight connection will result. Another important consideration when solder is used is that the solder selected be compatible with the pipe material to be soldered. For example, if copper fittings are used then 95-5 tin-antimony solder must be used as ordinary solder will not stand the high temperature that may occur.

If threaded unions are used then additional sealing with Teflon tape should be included. This should be done by tightly drawing the Teflon tape around the threads in such a way that it will not be undone as the fitting is threaded on. When using pipe tape or dope, two or three turns by hand followed by two or three turns with a wrench should secure the joint.

2.3.1 Structural Mounting Details

Each type of collector and each method of installation produces its own characteristics. The collector manufacturer should provide well illustrated mounting procedure guidelines. This section will deal with the various aspects of mounting collectors to sloped and flat roofs.

The majority of sloped roof installations will be on small residential houses which have wood as the roofing material used. When a collector is mounted on a sloped roof it can be either mounted directly to the roof or with a stand-off mounting structure if the pitch of the roof is

less than the desired pitch of the collectors. The loading requirements are basically limited to the dead load of the collector since the collector installation should not trap wind or snow which would increase the live load. Directly mounted collectors can be attached to the roof in several ways, with the selection dependent on the mounting hardware supplied with the collector. With shingle roofs, the collector support points can be anchored to a plate which spans the roof joists or to wooden sleepers or metal channels which are mounted directly on the roof. When sleepers or metal channels are used, they should not be installed across the slope of the roof or they will create a dam which would retain runoff and so allow water to penetrate the shingles. The sleepers and metal channels should run with the slope of the roof and if roofing cement is applied between each layer of shingles, under the sleeper and between the sleeper and the shingles, leaks should not occur.

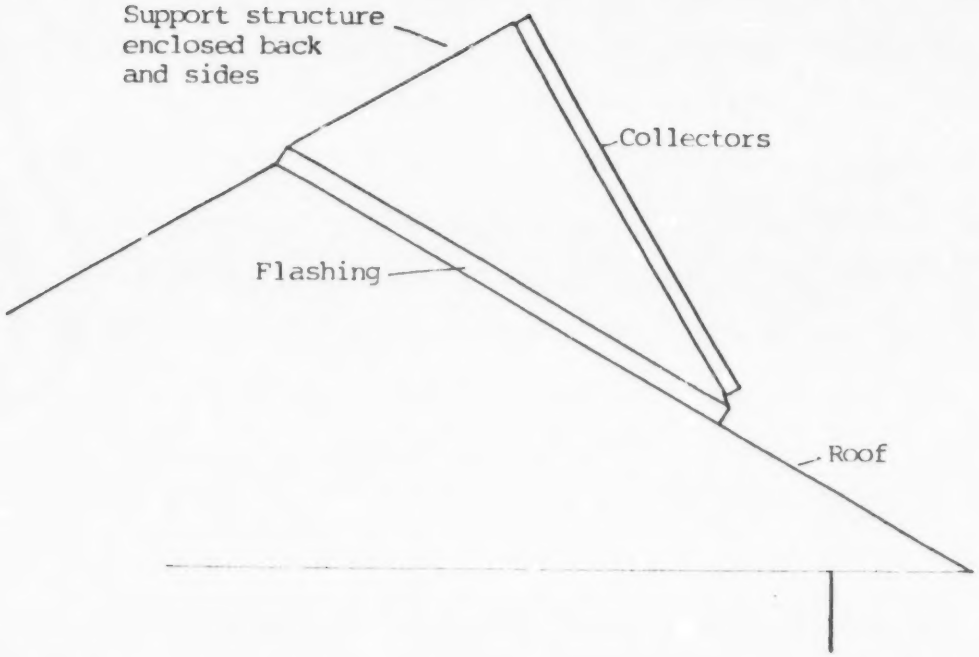
When the pitch of the roof does not meet the desired pitch of the collector, the collector should be mounted on a stand-off mounting structure. The design of the stand-off mounting frame will require many of the same considerations that are encountered with flat roofs, these factors will be discussed later. After a stand-off mounting structure has been installed it should be enclosed with weathertight sheathing and have waterproof flashing at the roof surface. This is done to prevent snow from collecting behind the collectors, and because it would be shaded, it would freeze more quickly and thaw more slowly. By providing enclosed back and sides to the stand-off mounting the potential of live loads due to snow

accumulation is reduced. A simple illustration of a stand-off collector installation is shown in Figure 2.1.11.

The most common location for the larger solar projects has been on the flat roofs of industrial and municipal buildings. The distance between the collectors vertical supports that are anchored to the roof will be a function of the building's structural capacity to accommodate point loads. The orientation of the collectors to the building structure will also affect the arrangement of the collectors support structure. If the collectors run at right angles to the secondary building structure then the legs of the collector support structure could be located at regular intervals on the secondary building structure. If, however the collectors run parallel to the secondary members then the collector's vertical supports must be located directly over a single secondary member. This results in either the member supporting the total load or in an additional structural frame being required above the roof to carry the collector supports.

Collector support structures can be built from preservative treated wood, or from pipes or angles made of aluminum, iron or steel. The structure should be strong enough to withstand the wind forces, the snow load and the dead weight of the collectors. Structures on flat roofs should be constructed so as to elevate the base of the collector above the average level of snow accumulation.

For collectors mounted on flat roofs a different type of collector support structure and anchoring procedure is required than for sloped roof installations. On smaller buildings with a wooden building structure



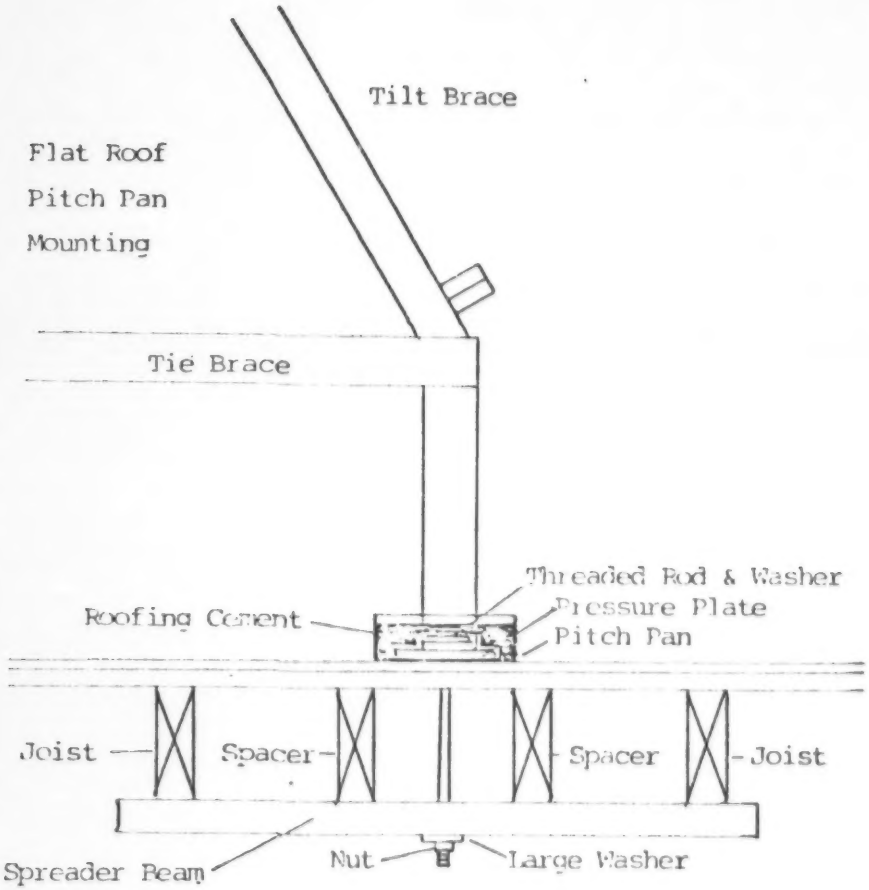
Enclosed stand-off mounting. The enclosed stand-off support structure may be shingled, covered with siding or painted to match the appearance of the building.

FIGURE 2.1.11

a pitch pan mounting can be used, as shown in Figure 2.1.12. Pipe column supports, as illustrated in Figure 2.1.13, should be used on the steel roofs while the curb support shown in Figure 2.1.14 should be used for collectors installed on a concrete roof. When curb supports are used their length should be kept to approximately 1.2 metres so that the curbs do not restrict rainwater movement. The pipe column and curb supports shown in Figure 2.1.13 and 2.1.14 are the recommended support methods given in Public Works Canada publication Structural Design for Solar Collectors, Briefing Document S-2.

A wide variety of collector racks and collector support structures can be used. The simplest collector racks are those employed on small collector installations were only a few collectors are used to form an array. The rack shown in Figure 2.1.15 is typical of the collector racks supplied and recommended by collector manufacturers for a small collector array installation.

When a large collector array is used then typically a long span, triangular shaped structure is required. The most common frame material used is round aluminum tubing, square steel tubing and hot rolled standard steel sections. There is a tendency to select aluminum or steel tubular space frames which results in an aesthetically pleasing design but can be extremely costly and labour intensive. In general, hot rolled steel, wide flanged beams and steel angle structural support systems are less expensive. The dead load of these frames can have a significant impact on the building's structural integrity so that when a large mounting installation is required the appropriate structural experts should be consulted.



Typical flat roof pitch pan mounting. The underside of the pitch pan is buttered with roof cement before attachment to roof. After the lag screw or threaded rod is in place the pitch pan is filled with pitch or plastic roof cement. The fastening hardware is then completely covered to prevent water from getting down into the screw threads.

FIGURE 2.1.12

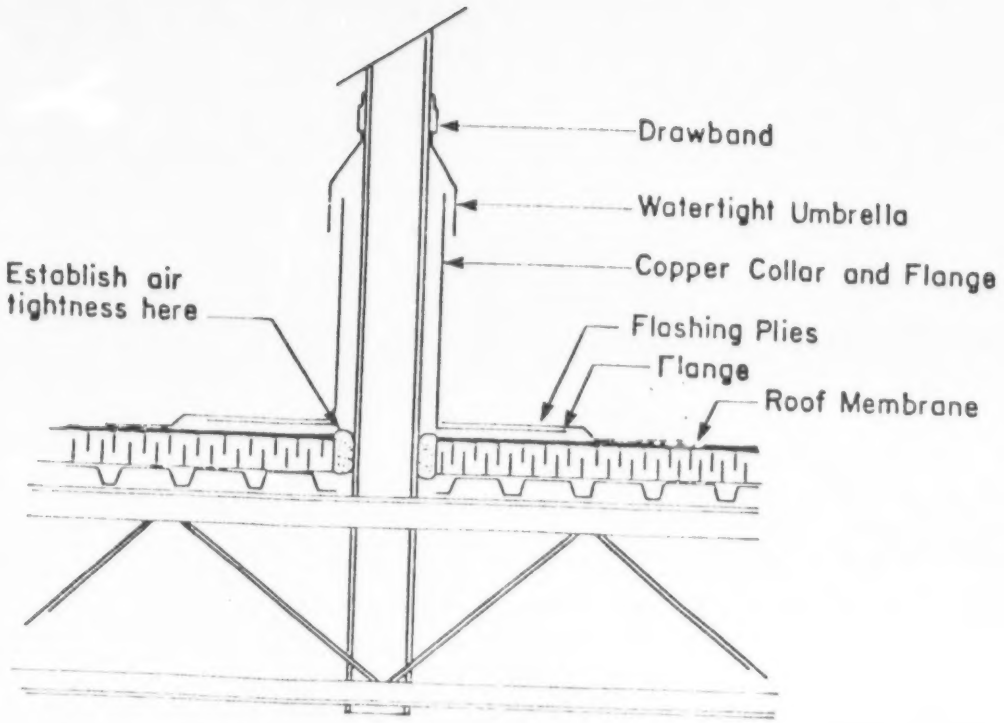


FIGURE 2.1.13

Pipe column support.

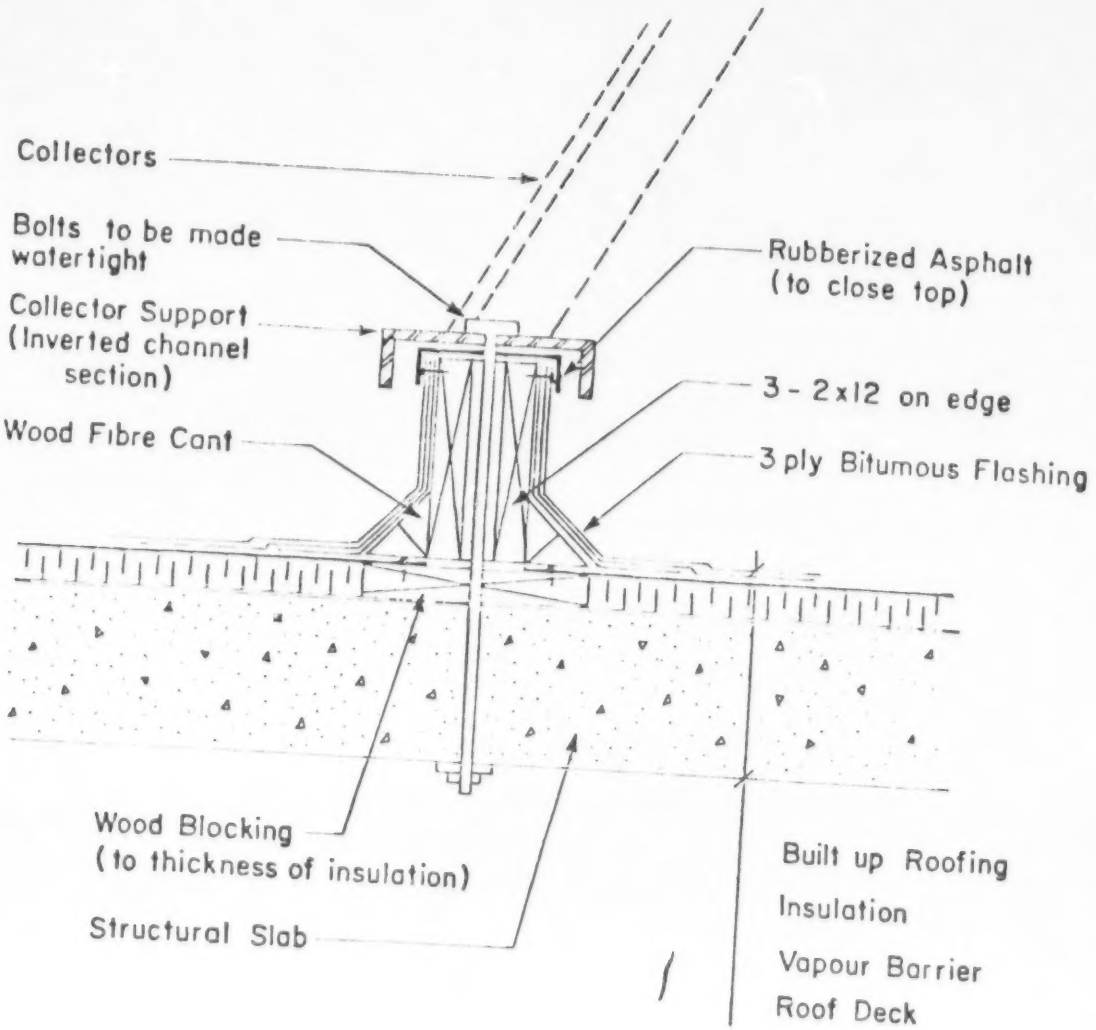


FIGURE 2.1.14

Curb support.

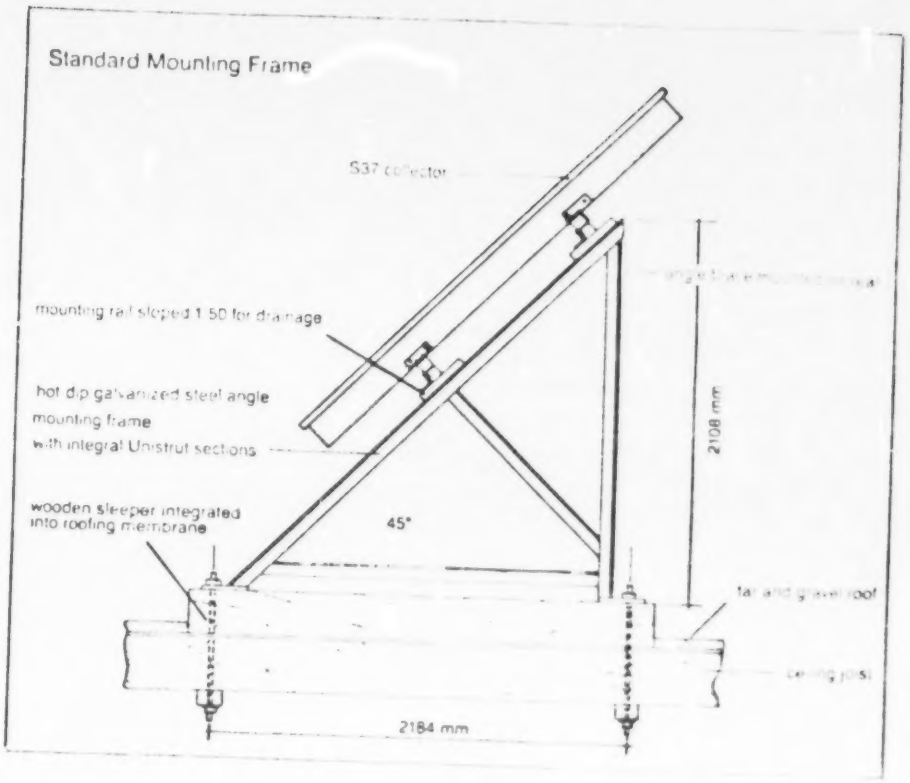

Standard Mounting Frame
S37 collector
mounting rail sloped 1:50 for drainage
hot dip galvanized steel angle
mounting frame
with integral Unistrut sections
wooden sleeper integrated
into roofing membrane
45°
2108 mm
2184 mm

FIGURE 2.1.15

If several rows of collectors are installed one behind the other, then a rear surface sloping towards the next row of collectors should be constructed out of plywood sheathing. If this rear surface is painted white or covered with a reflective film it will reflect radiation onto the next row of collectors. This type of reflector improves performance and also reduces wind lift and wind chill on the row of collectors.

2.3.2 Pipe or Duct Installation and Methods of Protecting It From Weathering

Complete insulation of pipes and valves is essential for successful solar system performance. Unfortunately most of the insulations that designers deal with were not developed for the solar field. Three types of pipe insulation commonly used for solar heating systems are fiberglass, flexible closed cell forms and rigid forms of urethane and isocyanurate foam.

Fibreglass pipe insulation can be bought in both rigid and semi-rigid form. The semi-rigid form allows the fibreglass to be cut to shape for covering valves and fittings. The rigid fibreglass insulation cannot take the flexible shapes that are often required by solar installations. The rigid-fibreglass is good for long runs of piping but it is not suitable for exterior manifolded collector installations. The fact that fibreglass when wet makes a better conductor than insulator necessitates the use of a waterproof covering on exterior applications of fibreglass insulation. Fibreglass pipe insulation can be bought with a watertight and ultraviolet resistant jacket. Additional waterproofing in the form of waterproof

weather resistant tape should be used to seal the crack which occurs along the performed fibreglass insulation halves.

Flexible elastomeric (closed wall) insulations are available in very limited thicknesses and so a second layer is required for an improved R value. The flexible insulation is not affected by water as it is waterproof and can be used as its own waterproofing. However flexible elastomeric insulation is affected by the sun's ultraviolet rays. This type of insulation can be painted to protect against ultraviolet deterioration. If it is not painted, serious deterioration occurs within 6 months and failure will occur within a year.

The rigid foam insulation is roughly comparable in cost to rigid fibreglass for the same R value. Rigid foam insulation deteriorates when exposed to the high heat associated with stagnation, to minimize the risk of damage to the insulation a pipe wrap should be employed. Rigid foam is not readily affected by water but a mild acid can be created which will deteriorate the pipe if water is allowed to contact the rigid foam and pipe surface. Some rigid urethane and isocyanurate foams come with a PVC jacket. The PVC jacket offers some resistance to ultraviolet damage but it is advisable to use manufacturer's recommended protective coating for longer service. When sections of rigid insulation with a PVC jacket are glued together they form a waterproof shell.

The majority of pipe insulation suppliers offer various forms of protective jackets. The most common pipe jackets are composed of either fabric, aluminum or vinyl material. The fabric jacket is a glass-fabric and asphalt combination which provides a high melting point but is not

waterproof. An aluminum jacket with a underlying moisture barrier provides the best protection against ultraviolet degradation and physical abuse, and is water resistant. The aluminum jacket is recommended for piping systems having a fluid temperature range of between 0 and 400°F. The vinyl jackets are usually a vinyl/aluminum combination and can be used for a wide range of pipe temperatures. Final selection of a protective jacket will be dependent on the expected fluid temperatures in the pipe system and the cost and availability of the insulation jackets.

The level of insulation on pipe, ducts, and tanks in a solar energy system should be optimized in the same way as for any other design job. The only difference is that the designer is usually faced with the problem of trading off capital investment for insulation against annual cost for fuel, while in a solar energy system design, he is trading off alternative capital investments. Thus he does not have to speculate about future interest rates or fuel prices.

For example, on one commercial scale solar service water heating project, the marginal cost of another collector (installed) was $209.00/m², and the energy gain was 0.67 GJ/a per m², for a cost of $312.00 per GJ/year. The indoor piping was 40 mm in diameter. The insulation thickness could be increased from 25 mm to 50 mm for $10/m. This increase in insulation produced a saving of .049 GJ/a per meter, for a cost of $203.00 per GJ/a saved. Thus the addition of more insulation was a better investment in this case than the addition of another collector. When the same calculation was repeated for an additional 25 mm of insulation the opposite conclusion was reached.

When carrying out such analysis, the fact that some indoor pipe losses reduce heating costs should be taken into account. In the above case the losses were to a mechanical equipment room which required no heating.

In general, it will be found that the optimum insulation thickness on tanks is considerably greater than on indoor pipes, because the cylindrical geometry in the latter case causes a more rapid decrease of energy saving with thickness. Also, the optimum insulation thickness on outdoor pipes will be greater because of the greater temperature difference, although the higher cost of outdoor insulation exerts an influence in the opposite direction.

2.3.3 Ground Reflectance and Its Effect On Thermal Performance

Tables 2.1.3.1 and 2.1.3.2 list the albedo (reflectance in the solar radiation wavelength range) of several kinds of natural ground cover. Table 2.1.3.3 indicates how the albedo changes with incident angel.

Collectors in typical installations may face a wide range of man-made materials. Albedos for some of them are listed in Table 2.1.3.4. Many others can be found in various text and reference books on thermal radiation.

The problem with estimating surface reflectance is that the actual values will vary widely for materials with a single description. For example asphalt pavement is listed as having a reflectance of 0.07, yet

gravel is listed at .71, so that real pavements and real roofs can be anywhere between the two.

Luckily, the solar energy system design engineer is usually dealing with a retrofit situation. It is possible to get a good approximation of the reflectance of the materials in the field of view of a set of solar collectors by taking light meter readings at several times during the collector operating day and comparing the brightness with that of a surface of known reflectance on which bright sunshine is falling. The light meter must be appropriately shaded during both sets of readings.

In the field of view of the solar collectors, many may be fully or partially snow covered during the winter. It is then necessary to estimate the fraction of snow cover and the length of the snow season.

Obviously, there are great uncertainities associated with evaluating ground reflectance. However, the overall effect of this number on the performance of solar energy systems is not great. Figure 2.1.20, in the following section shows that the effect of increasing ground reflectance from 0.2 to 0.8 for the entire year is only a 4% increase in the energy gain of a double glazed collector at a 43° tilt, and 6% for a single glazed collector. Therefore the designer who makes the best possible estimate of ground reflectance on a month by month basis is not likely to introduce a major error into his FCHART prediction if his reflectance estimate is slightly in error.

TABLE 2.1.3.1

TYPICAL VALUES OF ALBEDO

Surface	Albedo, %
Snow, fresh	70-95
Snow, several days old	70
Dry dune sand	37
Moist dune sand	24
Wet grass in sun	33-37
West grass, no sun	14-26
Dry grass	15-25
Forest: pine, fir and oak	10-18
Ocean	2-7

TABLE 2.1.3.2

LATITUDINAL AND CONTINENTAL MEANS OF SURFACE ALBEDO OVER NORTH AMERICA

Latitude Zone (°N)	Prevailing Surface Type	Continential Surface Albedo (percent)				
		January 31			March 31	Summer
		Average Snow	Heavy Cover	Light	Average Snow Cover	
65-70	Tundra	82.8	82.8	82.7	82.8	16.1
60-65)	Tundra and	(67.3	67.3	58.2	67.3	15.6
55-60)	Conifer forest	(59.1	59.1	54.8	57.7	16.5
50-55)	Forest and	(50.3	50.3	45.8	48.0	14.6
45-50)	grassland	(46.4	48.9	28.4	37.6	14.8
40-45)	Shrubland,	(37.9	50.4	19.0	30.5	15.8
35-40)	cropland and wood-land	(28.5	40.8	16.0	21.1	16.5
	Continental mean	43.0	47.4	34.7	39.4	16.0

TABLE 2.1.3.3

ALBEDO OF A GRASS SURFACE (IN PERCENT) AT TORONTO

Hour (true solar time)	07	08	09	10	11	12
Sept. 9, 1961 (clear)	25.6	22.3	22.5	21.3	20.8	20.6
Sept. 26, 1961 (cloudy)	19.7	19.1	20.2	17.5	19.4	17.6
Hour (true solar time)	13	14	15	16	17	
Sept. 9, 1961 (clear)	20.8	21.4	22.8	24.2	25.3	
Sept. 26, 1961 (cloudy)	18.1	19.3	20.0	19.7	28.6	

TABLE 2.1.3.4

ALBEDOS OF SEVERAL MATERIALS

Tarnished copper	0.36
Asphalt pavement	.07
Red brick	.25
Clay	.61
Concrete roofing tile:	
uncoloured	.27
brown	.09
black	.09
Bare earth, plowed	.62
Gravel	.71
White marble	.54

2.3.4 The Incident Angle Modifier

The incident angle modifier is a correction factor introduced to account for the variation of $(\alpha\tau)$ with the angle of incidence of the radiation falling on the collector. It is defined as

$$K_{\alpha\tau}(\theta) = (\alpha\tau)_{\theta} / (\alpha\tau)_{n}$$

where $(\alpha\tau)_{\theta}$ is the value of $(\alpha\tau)$ measured at the angle of incidence θ and $(\alpha\tau)_{n}$ is the value measured at normal incidence.

ASHRAE Standard 93-77 specifies the method of measurement of the incident angle modifier. It can be determined in an indoor or an outdoor test, and is found by making efficiency measurements at four different incident angles with the collector coolant inlet temperature equal to the ambient temperature.

Figure 2.1.16 shows typical curves of incident angle modifier as a function of incident angle for three flat plate collectors.

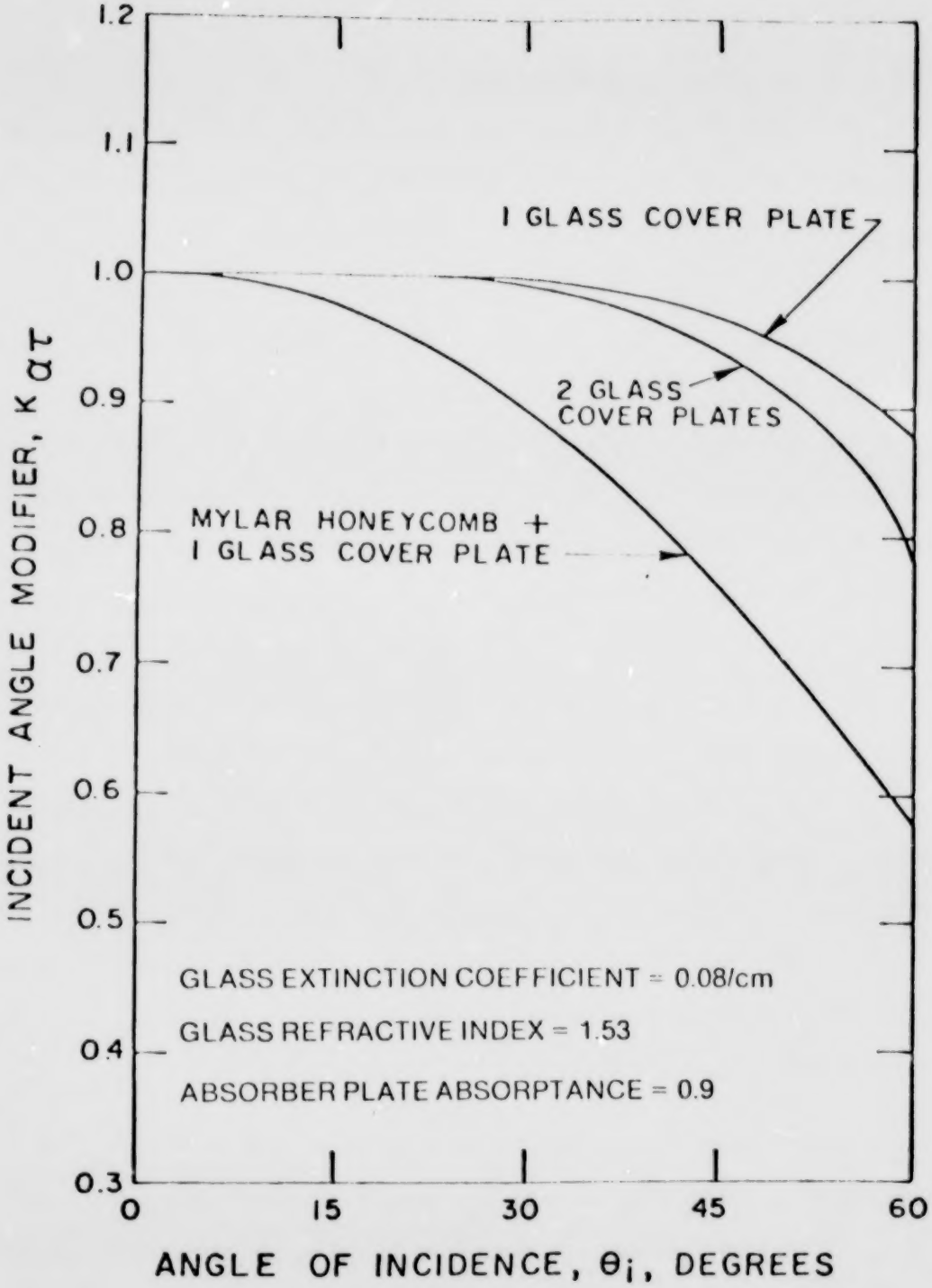
It has been found that the variation of the incident angle modifier can be made linear if it is plotted against $\frac{1}{\cos\theta} - 1$ instead of against θ. Figure 2.1.17 illustrates this method of presentation.

This formulation is convenient for computational purposes because it allows the incident angle modifier to be expressed as

$$K_{\alpha\tau} = 1 + b_{o}\left(\frac{1}{\cos\theta} - 1\right)$$

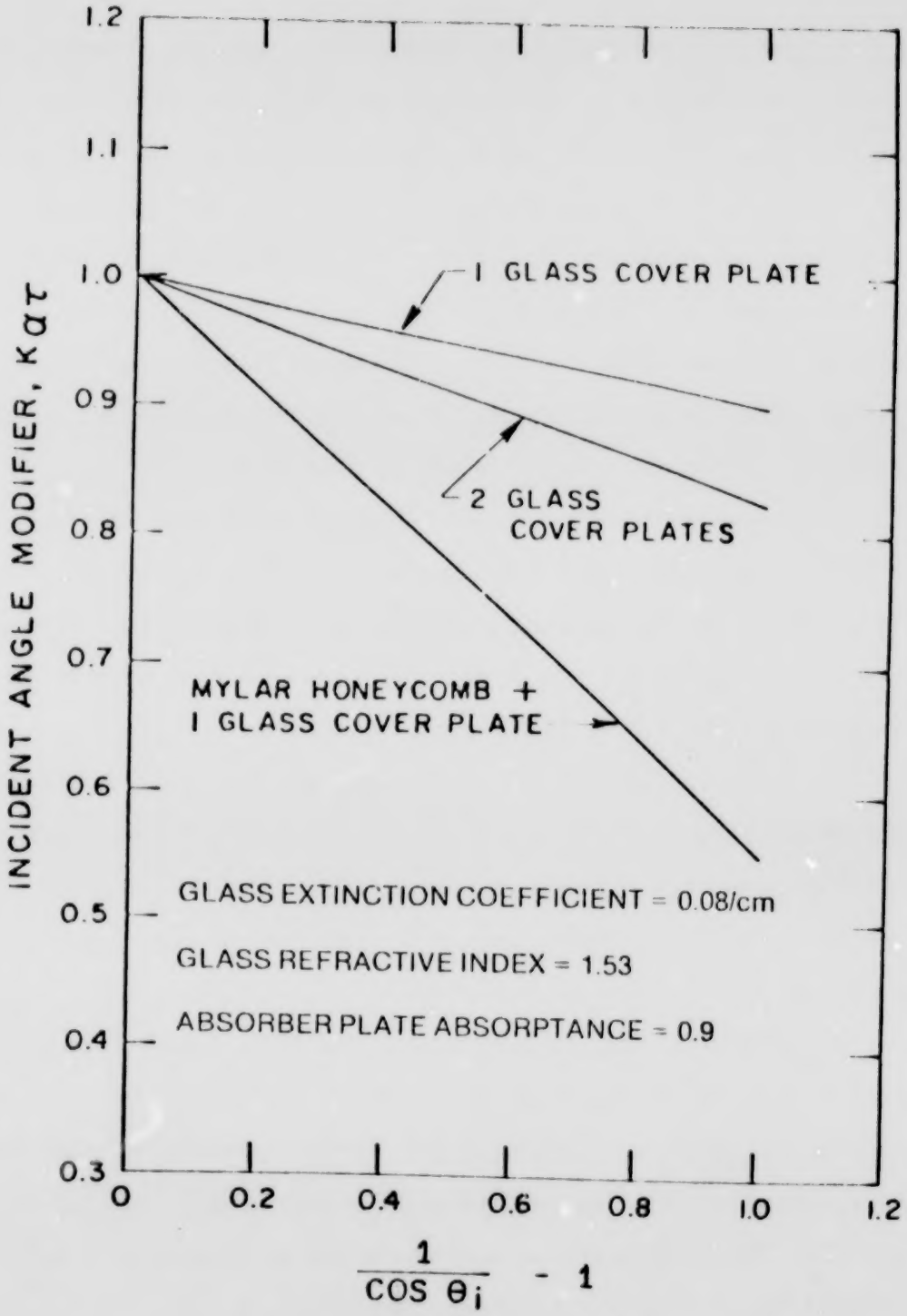
and a single number, the incidence angle modifier coefficient, b_{o}, is sufficient to define the value of $K_{\alpha\tau}$ for all incident angles.

At first glance, the reduction in collector efficiency caused by non-normal incidence does not appear serious. At 45°, a double glazed



Incident Angle Modifier for Three Flat-Plate Solar Collectors with Non-Selective Coatings on the Absorber

FIGURE 2.1.16



Incident Angle Modifier for Three Flat-Plate Solar Collectors with Non-Selective Coatings on the Absorber

FIGURE 2.1.17

collector loses only about 6%, and at 60°, only about 22%. However, it should be remembered that these corrections are made by subtracting from the efficiency at normal incidence, not by multiplying. Thus, if the efficiency of a certain double glazed collector at normal incidence and with the inlet temperature equal to the ambient temperature is 72%, the efficiency at an incident angle of 60% is 72% x 78% = 56%, and the efficiency at all other values of $(T_{f,i} - T_a) / GT$ is also decreased by an absolute amount of 14%, not by 14% of what it would have been at normal incidence. This point is illustrated in Figure 2.1.18.

Two other factors make the off-normal performance of a solar collector significant. One is the sun's declination. For a collector tilted at 45°, the incident angle will be greater than 20° even at noon, both in mid-summer and in mid-winter. This means that very little collector operating time will be spent in the range of incident angles for which $K_{\alpha\tau} = 1$. The second factor is that diffuse radiation is received over a wide range of angles of incidence. Figure 2.1.19 shows the effective incidence angles for isotropic diffuse radiation from sky and ground as functions of collector slope. The bands shown cover a wide range of single and double glazed flat plate collectors.

An examination of Figure 2.1.19 shows that an effective incidence angle of about 58° is a good approximation for sky diffuse radiation over a wide range of collector tilt angle. For diffuse radiation from the ground, the variation of effective incident angle is much greater than for sky radiation. To obtain a precise estimate of the performance of a collector tilted at 30° or more it will be necessary to use the data from this figure

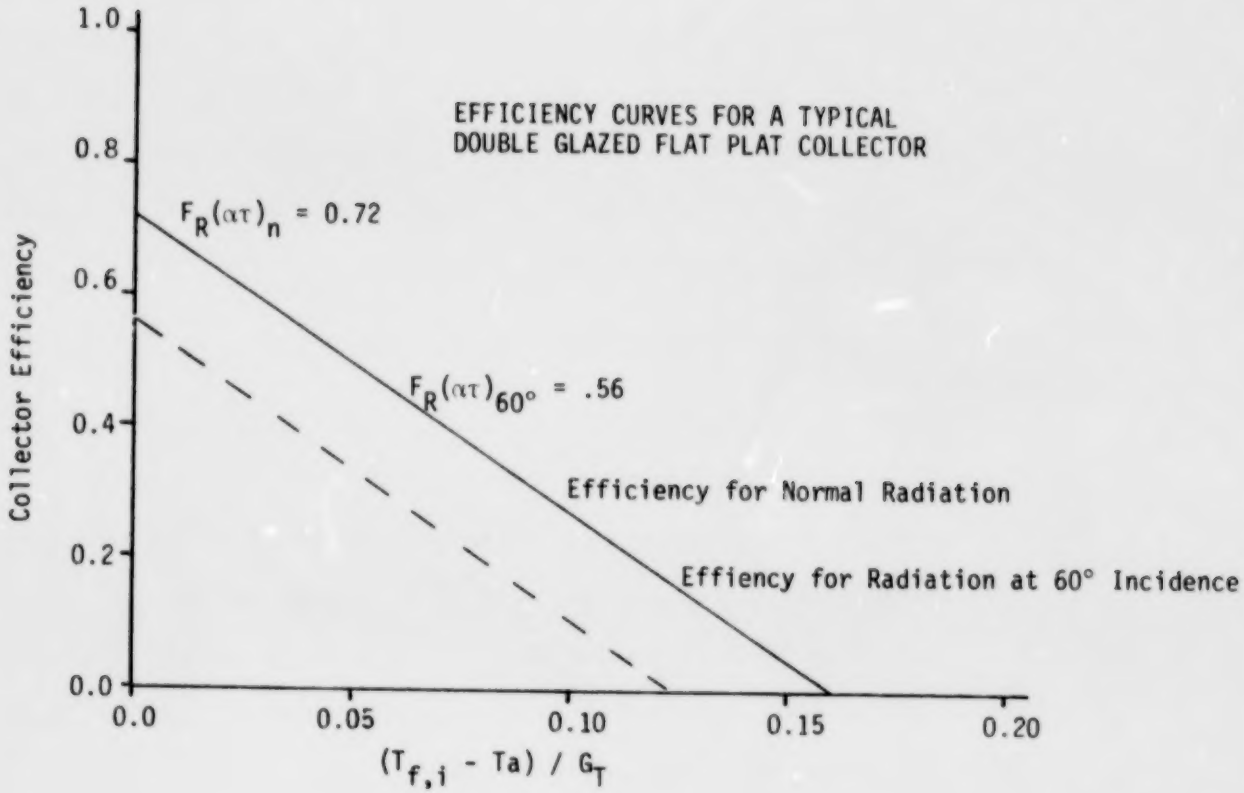


FIGURE 2.1.18

EFFECT OF INCIDENT ANGLE ON EFFICIENCY

along with the incident angle modifier. This is particularly true during the winter, when the ground is brighter than the sky and the accuracy of ground reflected radiation calculations is more important.

When FCHART is used by the design engineer to analyse the performance of a solar energy system using flat plate collectors, he can either supply the computer with the measure value of the incident angle modifier coefficient, b_o, or he can allow the value to be estimated from the number of covers, the index of refraction, the extinction coefficient and the thickness of the covers. In the latter case, the value of $K_{\alpha\tau}$ for each incident angle, θ, is determined from

$$K_{\alpha\tau} = \frac{\alpha \cdot \tau}{[1-(1-\alpha)]\rho d} \cdot \frac{1}{(\tau\alpha)_n}$$

with the reflectance and absorbtance of the covers calculated from the Fresnal equation and Bouger's laws for the value of θ being considered. The variation of the absorbtance of the absorber plate with θ is estimated from an empirical fit to data measured for blackened surfaces.

To calculate $K_{\alpha\tau}$ for diffuse radiation from the sky, the same method as for beam radiation is used, with an assumed incident angle of 60°. For ground reflected radiation the equation

$$\bar{\theta}_r = 89.8° - .57883\beta + .002693\beta^2$$

is used to determine the effective incident angle. This equation fits the curve of Figure 2.1.19.

Evacuated tube collectors differ markedly from conventional flat plate collectors in their response to non-normal radiation. They are not isotropic, and they do not conform to the usual incident angle modifier

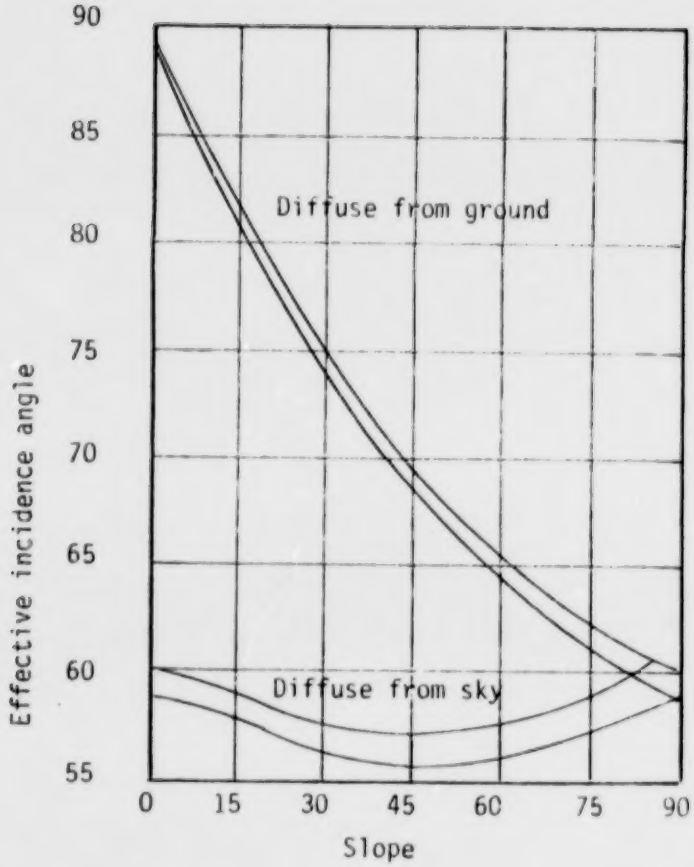


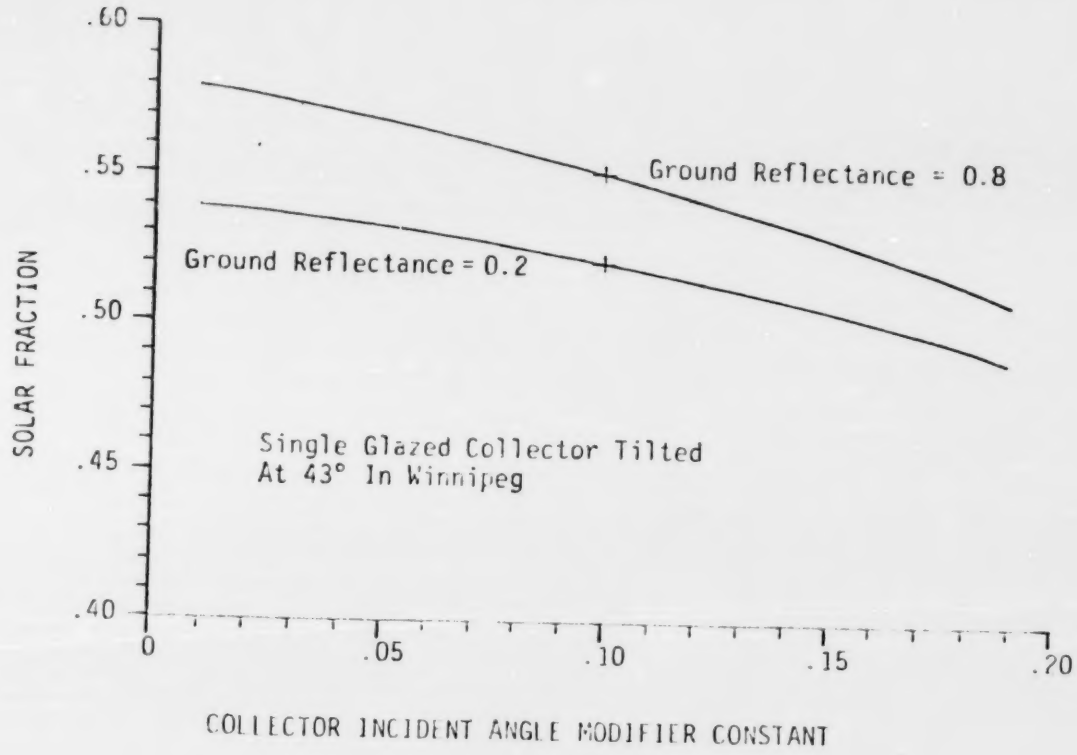
FIGURE 2.1.19

EFFECTIVE INCIDENCE ANGLE OF ISOTROPIC DIFFUSE SOLAR RADIATION

equation. In fact, $K_{\alpha\tau}$ may rise above 1.0 for non-normal incidence. Neither the ASHRAE 93-77 test procedure nor the FCHART computer program deal adequately with this type of collector. The manufacturers have made protests to the ASHRAE 93-77 Revision Committee, and it is possible that a new method of dealing with this problem will be included in the revised version of the standard.

The collector incident angle modifier equation is also inadequate to deal with concentrating collectors of either the imaging or compound parabolic type.

Figure 2.1.20 indicates the impact of the incident angle modifier constant, b_o, on the solar fractions predicted by FCHART. The points marked on each curve are typical values of b_o for single and double glazed collectors respectively. The range of values of b_o shown is far greater than could actually occur. As can be seen from the graphs, variations of b_o of ±50% cause about ±2% changes in the amount of energy collected by a single glazed collector and ±4% changes for a double glazed collector. As would be expected, a very high value of ground reflectance makes a collector more sensitive to variations in b_o.



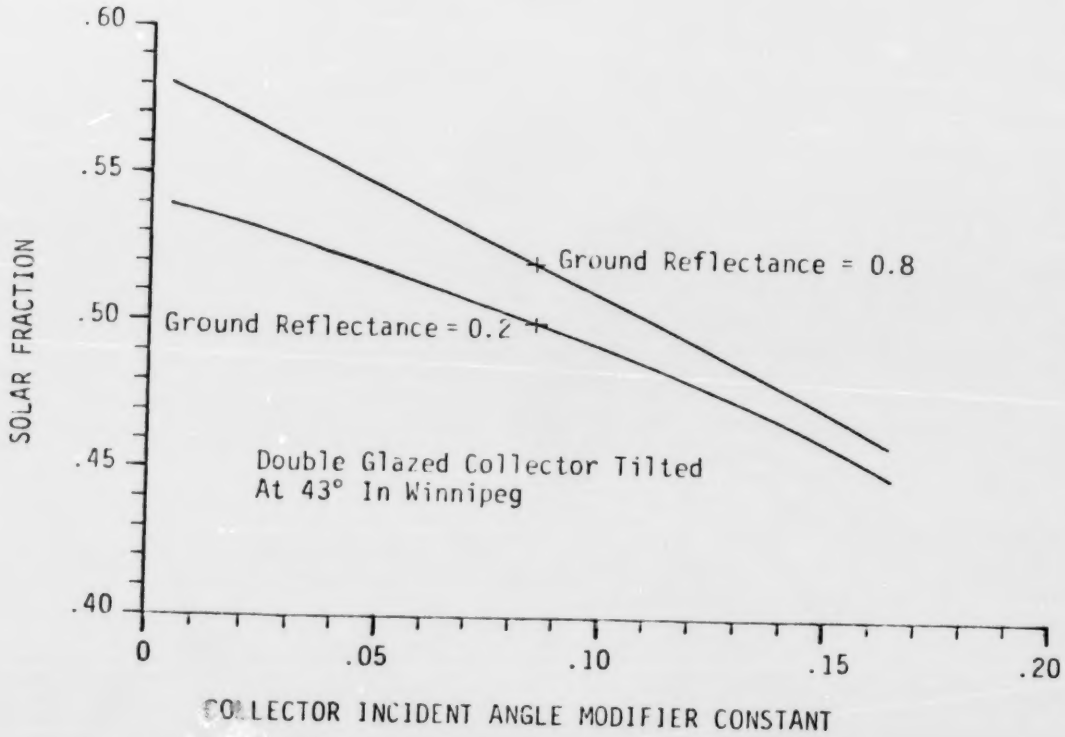


FIGURE 2.1.20

THE EFFECT OF SINGLE VS. DOUBLE GLAZING ON SOLAR FRACTION

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CHAPTER 3

DESIGN APPROACH

3.1 INTRODUCTION

The topics covered in this chapter are:

1. Design Sequence
2. Design Objectives
3. Thermodynamic factors
4. Economic factors
5. Synthesizing these factors into a system design.

In this chapter some of the fundamental concepts that help the designer to develop a successful solar energy system design will be identified. No attempt will be made to deal with all the detailed problems of component design faced by the engineer. Rather, an overall perspective will be taken, and the general approaches that enable the system designer to produce a successful product will be identified.

3.2 DESIGN SEQUENCE

The design of a solar energy system depends on the use to which the energy collected is to be put, and on the physical environment in which the system must operate.

Criteria used in reviewing the potential applications of solar energy in a facility are:

1. the grade of energy necessary to meet the load,
2. the size of the load,
3. annual load profiles,
4. daily load profiles,
5. the convenience of the load,

The first and most important of these factors is the grade of energy (i.e. the load temperature) required for the application. High temperature applications will have high costs per unit of collector area installed and low operating efficiencies. Conversely, low temperature applications can utilize low cost components and achieve high efficiency. For example, a ventilation air preheat system may have unit energy costs of an order of magnitude lower than a space heating system delivering an equal amount of energy.

The size of the load is also very significant. There are many fixed or semi-fixed costs associated with a solar energy system regardless of its size. A large load justifies a large system. A large system provides a larger base to support these fixed and semi-fixed costs. A solar energy system meeting a moderate fraction of a load will operate at relatively high efficiencies when compared to one meeting a large fraction of the same load. A large load presents the opportunity of installing a solar system large enough to enjoy economies of scale, while small enough, relative to the load, to operate efficiently.

Daily and annual energy application load profiles should be compared to solar availability. High summer loads and low winter loads occurring during daylight hours are the ideal. Residential space heating, with large

night winter loads and no summer loads is on the negative side of the spectrum while beach-shower facilities are on the positive. The daily load profile is an indication of what the thermal storage requirements will be. Thermal storage is often a major component in system cost, so systems that have no storage may show cost advantages in certain applications over those with storage.

The convenience of an application refers to the ease with which a solar energy system can be integrated into a thermal system. During the design stage, it is relatively inexpensive to modify a structure to support a solar energy system for a particular load application. In an existing structure, the most logical solar application may be too inconvenient and thus too costly to consider.

Once a building has been analysed and the "best" solar application selected, the designer should begin to conceptualize the layout of the system components. Rules of thumb tempered by physical constraints (such as the mounting area available for collectors) are used to select a collector area. Building-operator imposed constraints may further restrict the latitude of designer decisions.

In new construction, a building design can be modified to conveniently incorporate a solar energy system. Retrofit systems involve compromise and trade-offs. However, this does not necessarily mean the system will be much less efficient than an optimally located system. Variations of ±15° from ideal slopes and up to 45° from ideal collector azimuth angles frequently have very little effect on system performance, while allowing the designer to utilize existing building features to reduce system cost. The

designer should carefully assess the building's features when laying out system components, and attempt to simplify installation and operation of the system. Collector support structures, ducting and piping and thermal storage can account for a major feature of first costs. Working with, rather than around, building features can result in significant cost savings. As capital costs are the most significant part of the cost of solar energy, they should be controlled as much as possible.

Although capital costs should be kept low, this should not be done at the expense of unit energy costs and reliability. Some low cost systems experience a lot of down time. The cost of repairs and the smaller solar fraction met by the system (due to the unavailability of the system) may result in higher energy costs over the life of the system. Capital and operating costs for the various loads and system configurations should be compared to system performance. The most important parameter in selecting a solar energy system size and configuration is the $/GJ cost of useful energy collected. The designer should select a system that meets all the necessary design criteria while minimizing unit energy costs. This will not usually be the most efficient system possible for the application, but the system should be designed to operate at a high relative efficiency.

There are two areas of solar energy system design that may require analysis by a structural engineer. Roof mounted collectors may not present significant loads on the structure, by themselves. However, wind loads on the array or snow loads that accumulate on a roof because of the "snow fence effect" of the collector arrays may exceed structural capabilities of the building. Public Works Canada, Design/Construction Branch has issued

"Briefing Document S-2, Structural Design Solar Collectors" on the topic of roof mounted solar arrays. The high mass of thermal storage required for some solar energy systems may present structural problems. Generally, thermal storage must be located on structural floors or on slabs of grade.

Every solar energy project is unique and should be approached with an open mind. The solution to each job requires its own mix of economic, technical, space, reliability and aesthetic considerations. The designer should look for opportunities in the structure and the building energy requirements that will yield the lowest solar energy costs possible for the application.

3.3 DESIGN OBJECTIVES

The important objectives of a solar energy system designer are:

1. safety
2. reliability
3. durability
4. maintainability
5. performance/cost ratio

Safety is not an insignificant issue in solar energy systems. Low pressure hot water systems have killed many people and blown buildings apart when controls and relief valves failed. Professional engineers take on serious responsibilities when they design systems, and no engineer who is not qualified and experienced in the design of solar energy systems or other systems of a similar nature should undertake such a design. An engineer should carefully review the design, imagining each control element

has failed and each valve incorrectly adjusted, to check for possible unrelieved overpressure or overheating situations. As discussed earlier, contamination of potable water is another potential hazard which must be guarded against.

When in doubt on a safety issue, a design engineer should imagine testifying at an inquest to justify or explain a decision.

Reliability, durability and maintainability are really part of system economics, but are discussed separately because it is so difficult to quantify their cost effectiveness. Experienced design engineers will have developed their own standards on these issues and will continue to get feedback from clients when they design systems that fail in these respects. On the other hand, few clients notice when a system is too expensive because the engineer put in a couple of unnecessary isolating valves, or wrote an unrealistic specification for a control component. A good engineer must monitor the design to ensure that systems are not overdesigned at the client's expense.

Codes and standards are one of the bases of design. Some important references which may be useful in designing solar energy systems are:

1. Government of Canada Master Construction Specification -

   Section 15643 - Flat Plate Solar Collector Panels - 1979-12-31.

2. ASHRAE Standards
   93-77 Flat Plate Collectors (presently under revision)

   95-81 Packaged Domestic Water Heaters

   96-80 Unglazed Collectors

(These ASHRAE standards are all standard methods of testing thermal performance)

3. CSA Standards

F378-1982 - Solar Collectors

F379-M1982 - Solar Domestic Hot Water Systems (Preliminary)

(These CSA standards include thermal performance tests and also requirements for safety and durability)

The solar domestic hot water system standards provide a good starting point for designers of larger solar service water heating systems.

In addition to the design objectives listed above, particular projects may have additional objectives such as system development, training and experience, or performance monitoring. The PUSH program has as its over-riding objective the establishment of a Canadian solar equipment industry. Designers of PUSH funded projects must keep this in mind when making cost-effectiveness trade-offs between investment in solar collectors and investment in conventional hardware which makes up the "balance of plant".

3.4 SYSTEM OPERATING RANGES AND COLLECTOR THERMAL PERFORMANCE

The thermal efficiency of a solar collector is a function of the ratio

$$(T_{f,i} - T_a)/G_T$$

where $T_{f,i}$ = entering fluid temperature

T_a = ambient temperature

G_T = insolation on the collector

This number will vary during a typical year from infinity almost to zero, and in some applications to well below zero. To select the right collector

the designer must match the collector performance curve to the curve of the frequency distribution of $(T_{f,i} - T_a)/G_T$.

Figure 3.3.1 shows two distributions of this ratio, for inlet temperatures of 5°C and 35°C using Winnipeg weather data and a south facing collector tilted at 45°. (In the real system, the inlet temperature normally varies too, but constant values have been used here to simplify the discussion.) Figure 3.3.2 shows two typical collector efficiency curves, for an unglazed plastic collector and for a glazed collector with a metal absorber.

By comparing the frequency distribution of $(T_{f,i} - T_a)/G_T$ with the collector efficiency curve, a distribution curve for the variation of collector efficiency throughout the year can be produced. Such a curve is shown in Figure 3.3.3, for the glazed collector with an inlet temperature of 35°C.

The curve in Figure 3.3.3 was produced from the curves of Figures 3.3.1 and 3.3.2 by the following means. For each valve of $(T_{f,i} - T_a) / G_T$ on Figure 3.3.1 the correponding frequency on the curve was 35°C inlet temperature was determined. For the same value of $(T_{f,i} - T_a) / G_T$ in Figure 3.3.2, the efficiency of the glazed collector was determined. Then each collector efficiency was plotted against the corresponding frequency in Figure 3.3.3. (For example, the dotted lines on Figures 3.3.1 and 3.3.2 show that, at $(T_{p,i} - T_a) / G_T$, the frequency of occurrence is 310/year, and the efficiency is 27%. This point is illustrated on Figure 3.3.3).

A curve of the frequency distribution of efficiency is of little use in the detailed design of a system, but it does have value in the concep-

FIGURE 3.3.1

Frequency Distribution of $(T_{f,i} - T_a)/G_T$

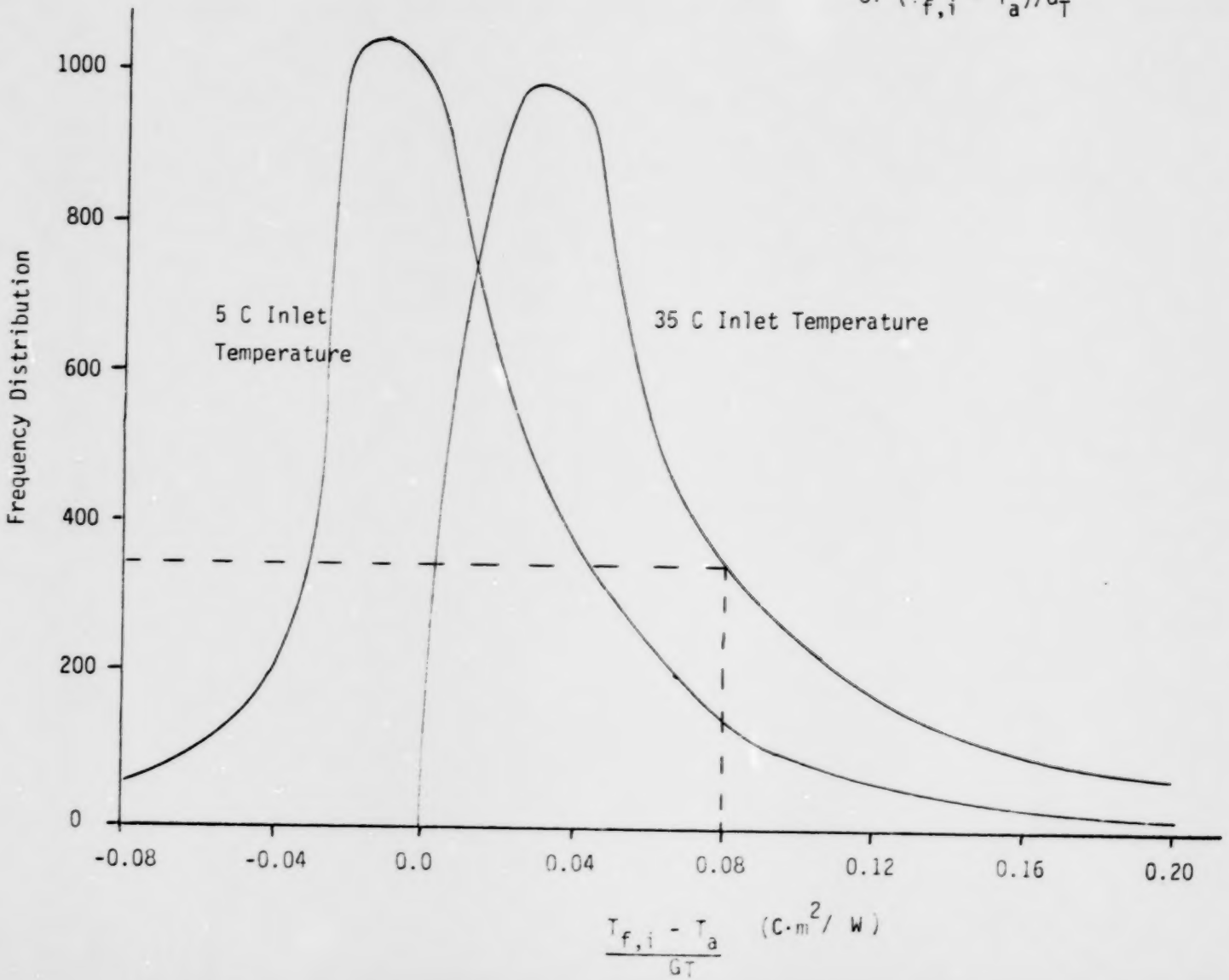


FIGURE 3.3.2

Efficiencies of Two Typical Collectors

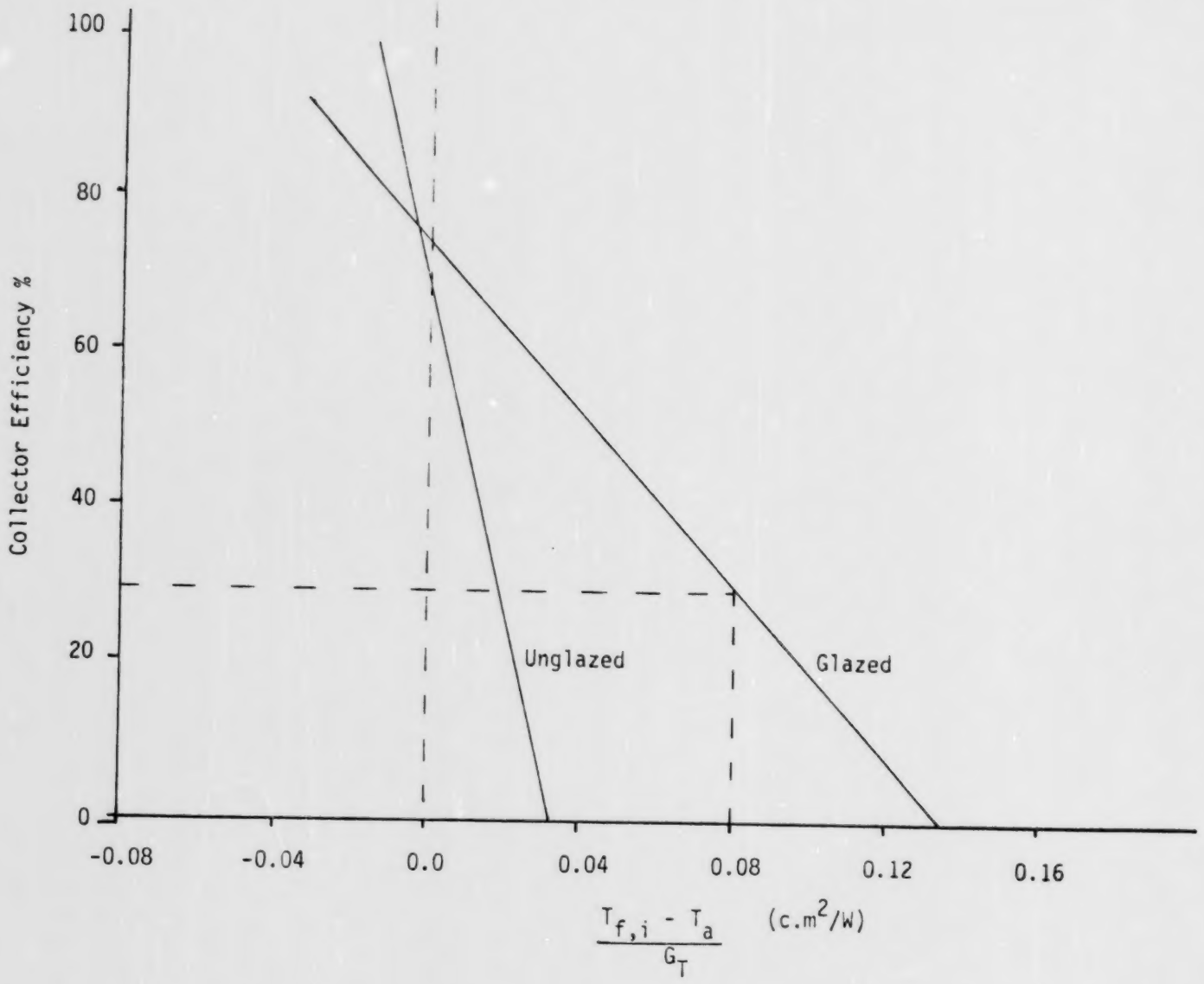


FIGURE 3.3.3

Frequency Distribution of Efficiency

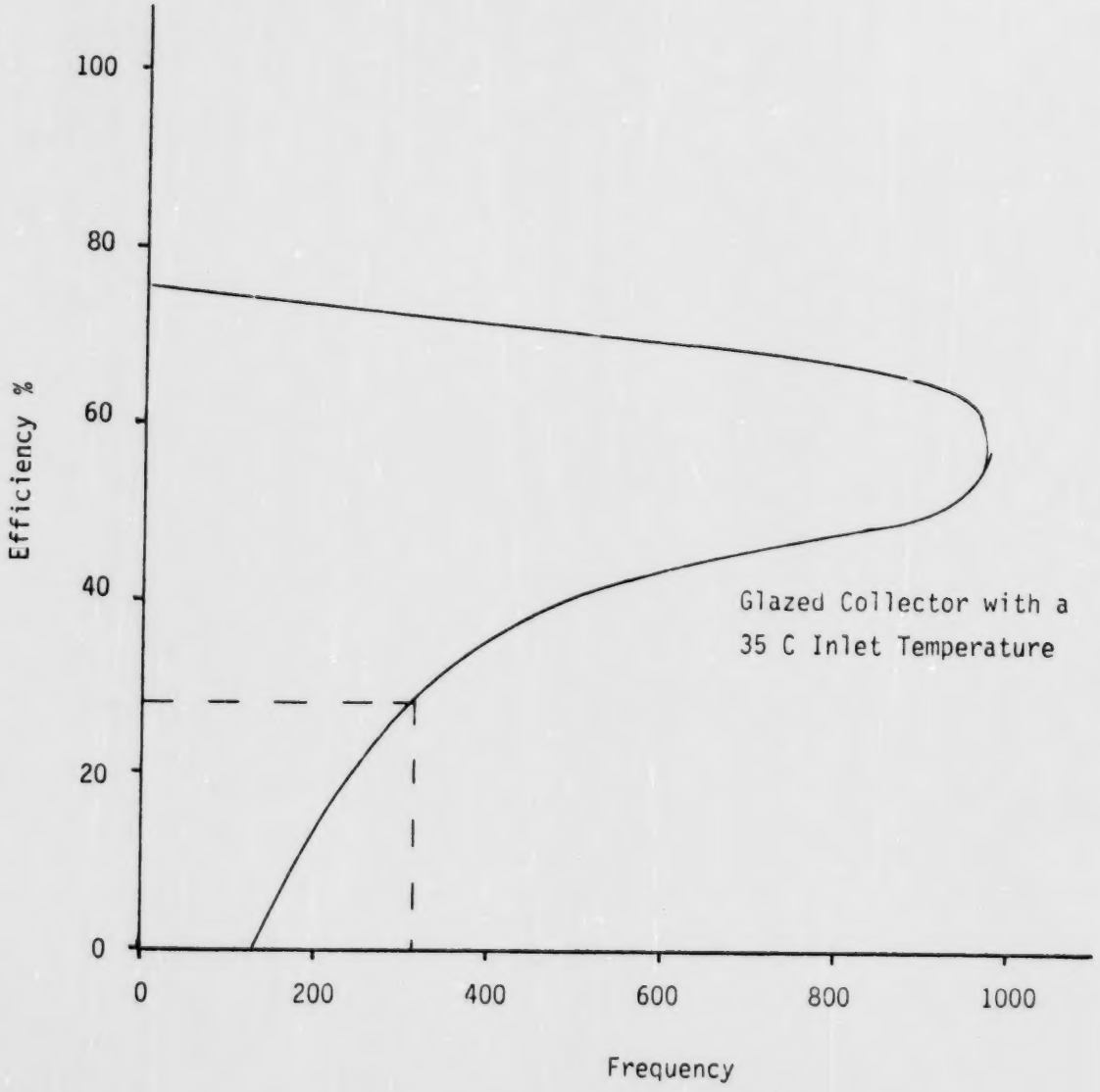


FIGURE 3.3.4

Frequency Distribution of Efficiency
for a 5 C Inlet Temperature

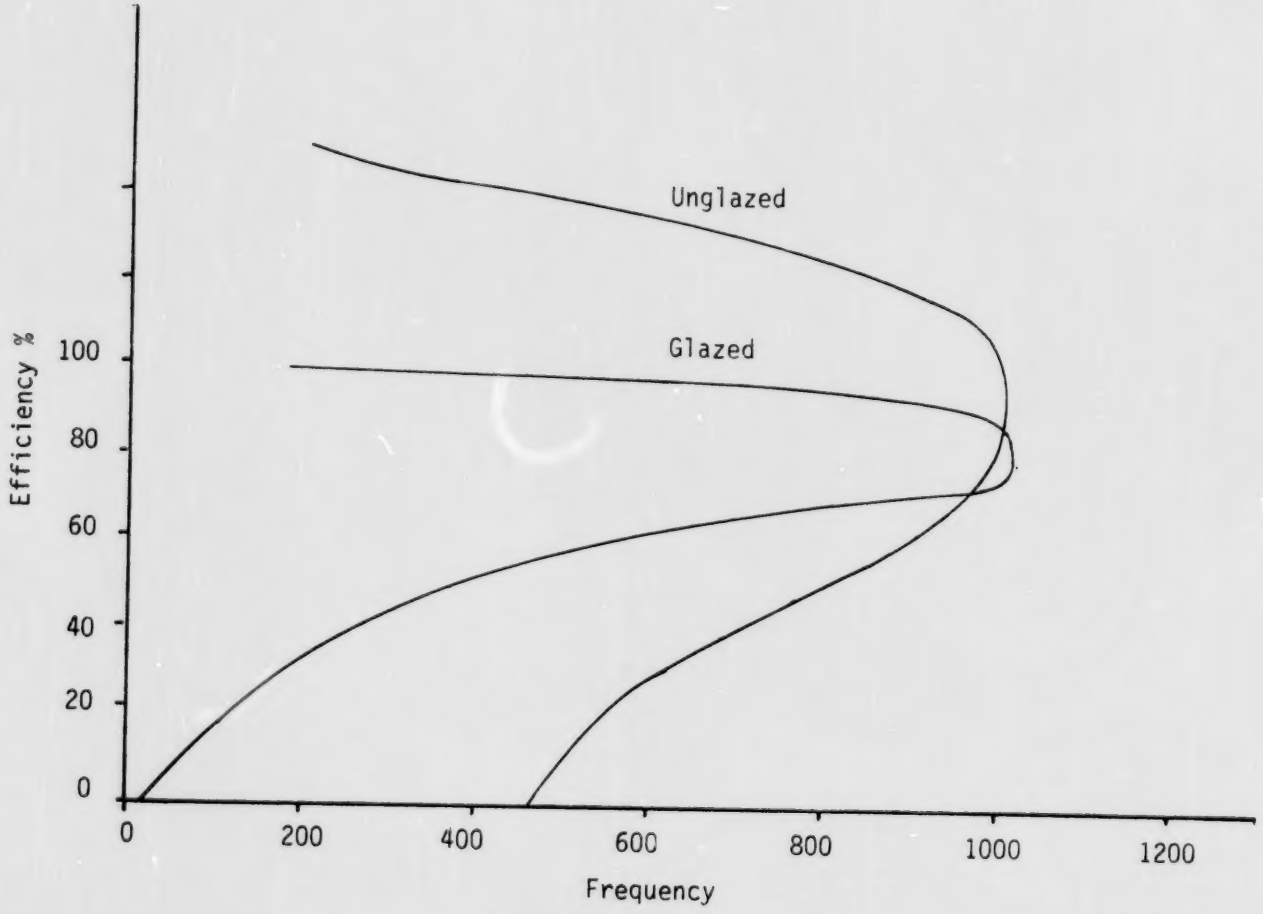
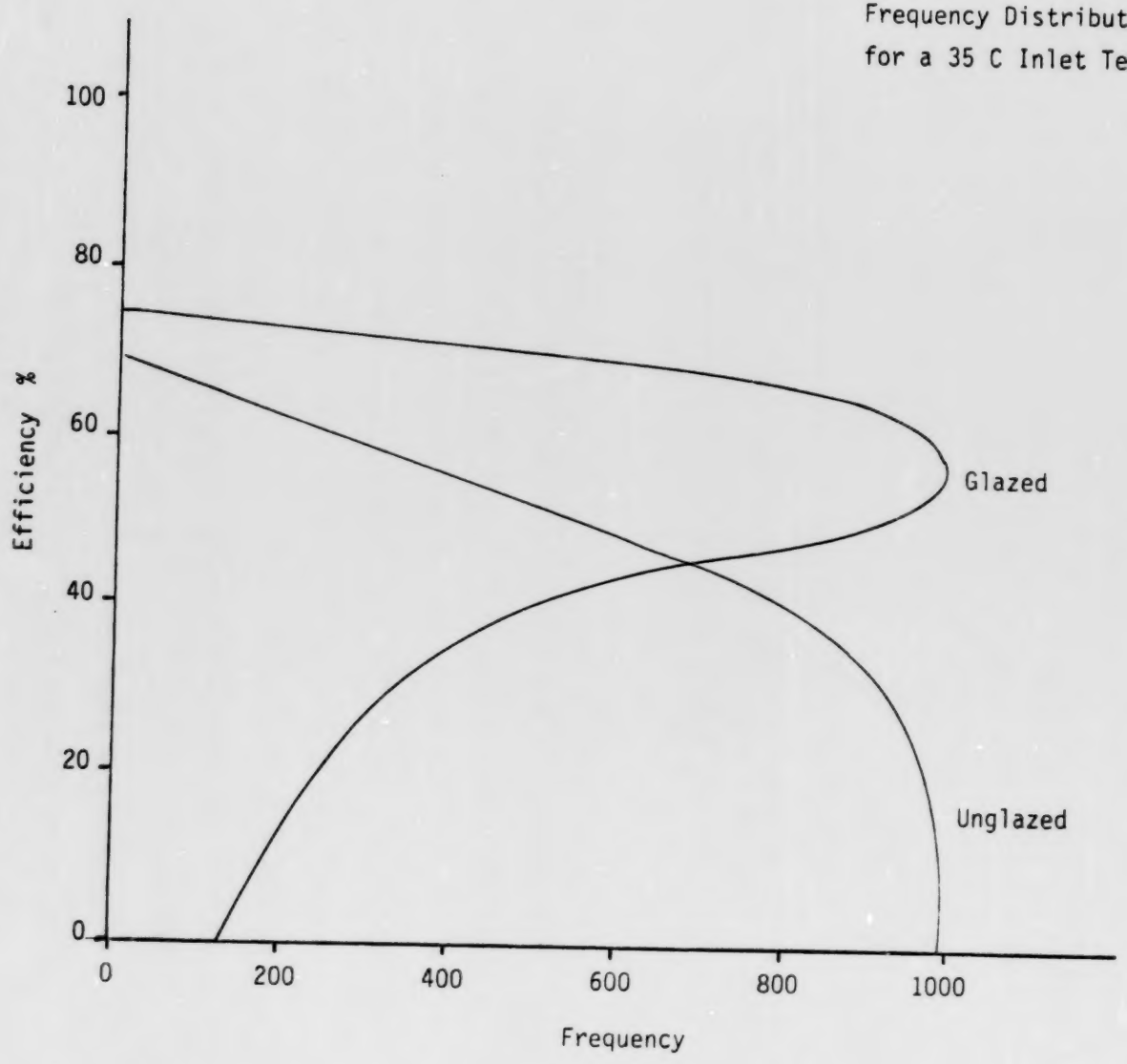


FIGURE 3.3.5

Frequency Distribution of Efficiency
for a 35 C Inlet Temperature



tual design stage, and in arriving at an appreciation of why a particular collector may be best in a given situation. For example, to find the collector with the best range of thermal efficiencies for a given job, a comparison can be made between the efficiency distributions of those collectors being considered. In Figure 3.3.4 and Figure 3.3.5, the two collectors are compared for each of the two loads. As would be expected, the unglazed collector has the best range of efficiencies when the inlet temperature is low and the glazed collector is best when the inlet temperature is higher.

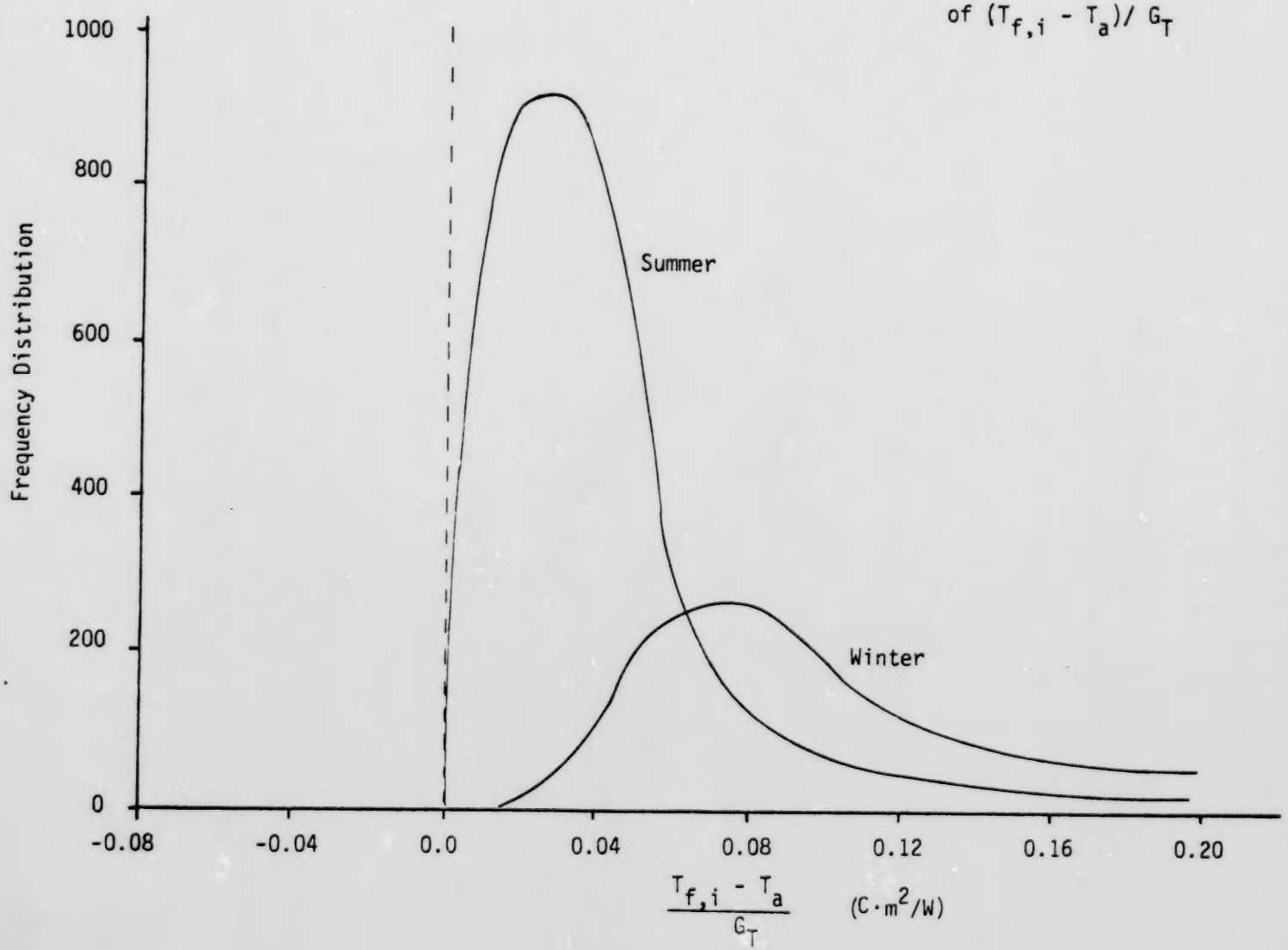
If the same comparison were made at even higher inlet temperatures it would be found that the evacuated tube collector, which has a lower $F_R(\alpha\tau)$ and also a lower $F_R U_L$ than a glazed collector, would have the best range of efficiencies.

This approach to visualising performance can also be applied to the evaluation of collectors for seasonal applications. Figure 3.3.6 shows a frequency distribution of $(T_{f,i} - T_a)/G_T$ split into two separate distributions, for summer and for winter. Obviously, the best collector for one period will not be best for the other. For example, it is likely that for a process water heating application that could be best served by a glazed collector if the load were constant throughout the year, the best collector to serve the same load from May to September might be an unglazed plastic collector, while the best collector to serve that load in the winter might be an evacuated tube collector.

The frequency distribution of collector efficiency provides a useful insight into the performance of collectors in various applications.

FIGURE 3.3.6

Frequency Distribution of $(T_{f,i} - T_a)/ G_T$



However it does not provide a quantitative comparison to the designer. One reason is that in real applications the inlet temperature varies. Another is that the efficiency distribution must be weighted by the insolation distribution to determine the annual performance. Thus the designer must use a simulation program to determine the actual performance of a particular collector for a particular load. The above discussion only provides insight into which collectors may be worth considering for a certain application.

Another issue not considered in this discussion is collector cost. The real issue in selecting a collector is not the amount of energy collected per square foot but the amount of energy collected per dollar invested.

3.5 EFFECTS OF FLOW RATE AND FLUID PROPERTIES ON THERMAL PERFORMANCE OF COLLECTORS

The Canadian Solar Industries Association's Solar Product Data Sheets show the thermal performance curves for solar collectors determined according to the test method described in ASHRAE Standard 93-77. These tests are carried out using the coolant specified by the manufacturer, normally water, and at a single flow rate specified by the manufacturer.

The optimum solar energy system design for a particular application seldom requires the flow rate per collector specified by the manufacturer. Also, in many designs, the coolant is not water. Both these variations change the collector efficiency curve. However, to do this precisely requires a calculation of the flow regime and the heat transfer

coefficienct in the collector, and this is time consuming. To assist the design engineer, the Solar Programs Office has produced a Technical Note (No. 2, June, 1982) entitled "Adjustment of Thermal Performance Curves for Variations in Flow Rate and Fluid Characteristics of Solar Collectors". In this note, graphs of $F_a = F_{R\ (collected)} / F_{R\ (test)}$ are plotted against flow rate of water, propylene glycol and ethylene glycol for several PUSH approved collectors. Figure 3.4.1 shows such a graph for a Solarsystems Sol-100 collector.

If, for example, a designer who wished to use propylene glycol circulating at 2 L/min in this collector would read a value of $F_a = .97$ from Figure 3.4.1, and then calculate

$F_R(\alpha\tau) = .97 \times .66 = .64$

and $F_R U_L = .97 \times 4.0 = 3.88\ W/M^2°C$

Since new collectors are being developed and existing ones are sometimes retested, the Solar Programs Office has produced another Technical Note (No. 3, June 1982) entitled "Calculation of a Flow Rate and Fluid Property Correction Factor for Collector Performance Curves." This note tells the design engineer how to calculate F_a for a collector that is not included in Technical Note 2, or for a flow rate or fluid not covered.

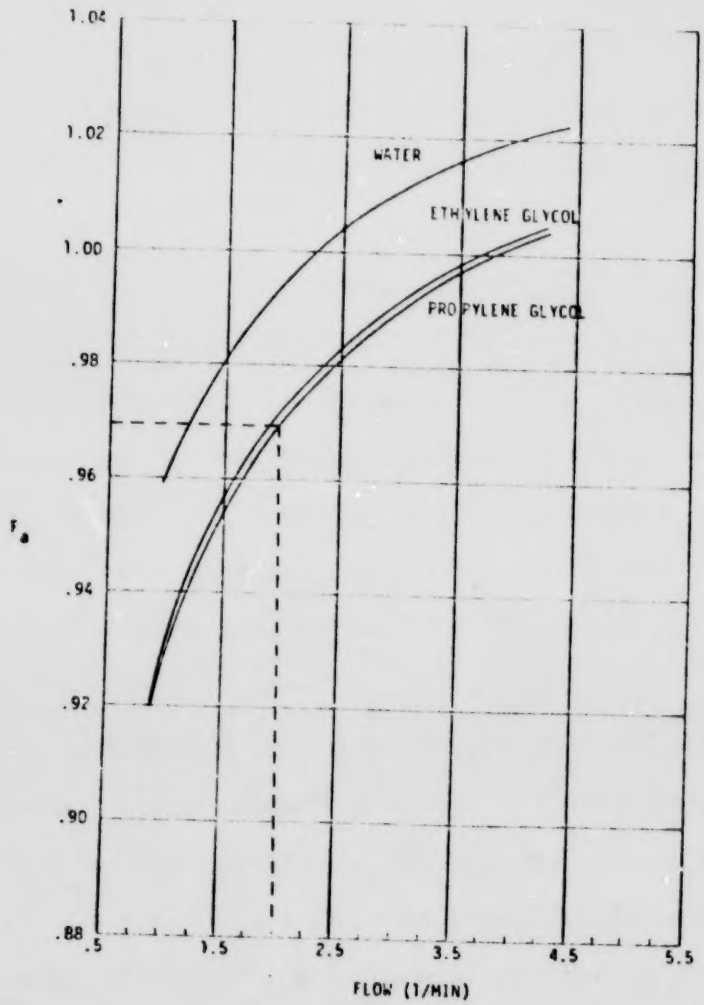
3.6 EFFECT OF WIND SPEED ON COLLECTOR EFFICIENCY

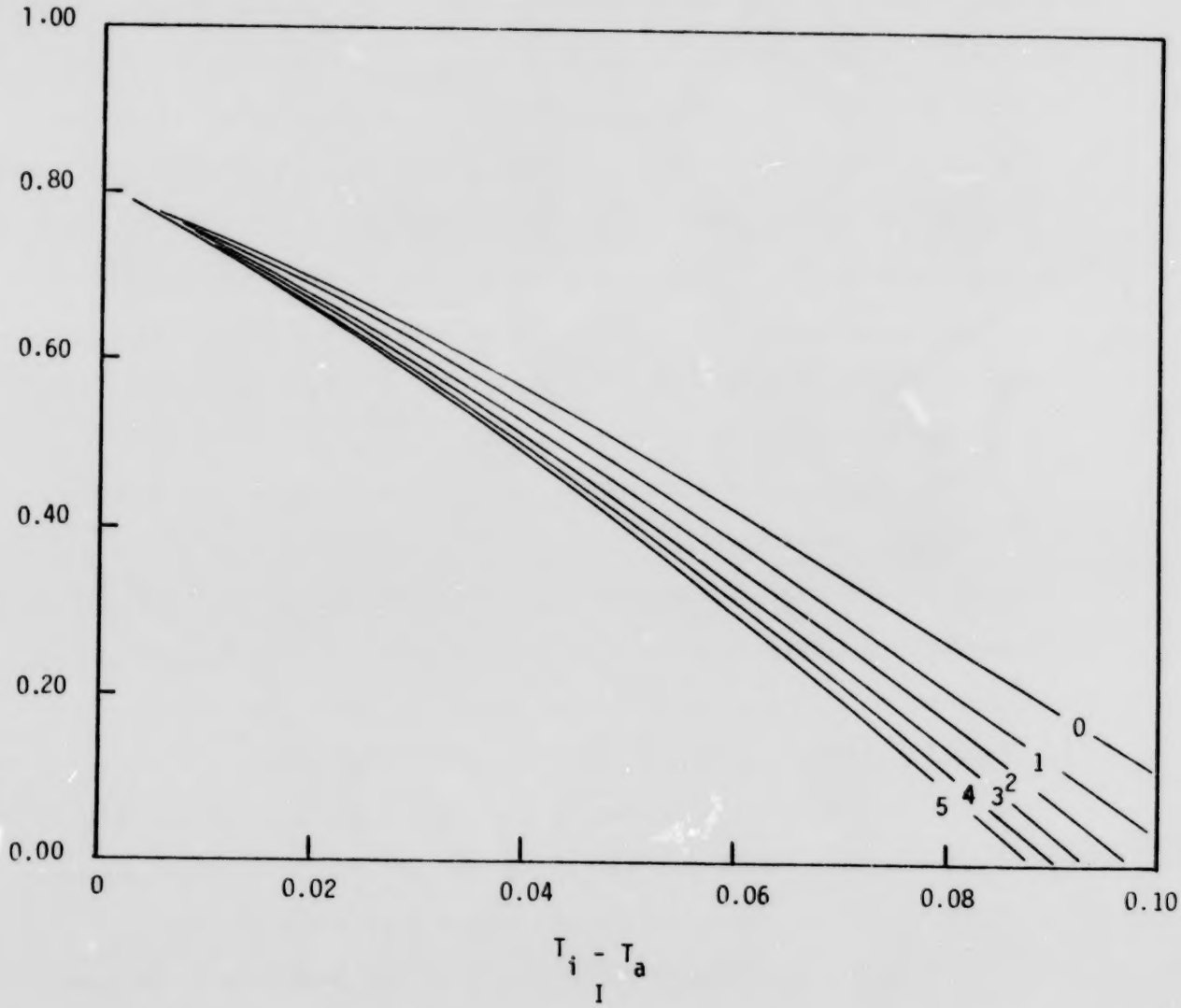
The efficiency of a solar collector is strongly influenced by the wind. A flow of air over the outer cover glass (or over the absorber of an unglazed solar collector) increases the plate-in-air heat transfer coefficient h_{p-a}, and thus increases the loss coefficient U_L. Figure 3.5.1

FIGURE 3.4.1

Solarsystems Sol-100 Single-Glazed Liquid Flat Plate

Test Data		Source of Information
Flow rate	2.3 L/min	.CSIA Data Sheet, 5 October 1980
Fluid	water	
Date of test	unknown	
$F_r(\tau\alpha)$	0.66	
F_rU_L	4.0 $W/m^2.°C$	





The Effect of Varying Wind Speed on the Efficiency Curve of a Typical Flat Plate Solar Collector

FIGURE 3.5.1

shows the effect of varying wind speed on the collector efficiency curve of a typical glazed flat plate collector.

The ASHRAE 93-77 Standard "Methods of Testing to Determine the Thermal Performance of Solar Collectors" requires that the wind velocity at the collector mid-height be measured and recorded, and that it be less than 4.5 m/s (10 mph). This data is presented in the Canadian Solar Industries Association's Solar Product Data Sheets as a range of wind velocities during the test. A review of this data shows that many tests were run in winds greater than that allowed by ASHRAE 93-77. Also, the range is so great in most cases than it gives little indication of how the data could be corrected for other wind velocities. This presents the designer with a serious problem, since according to Figure 3.5.1, the efficiency of a collector can vary from 0 to 20% even within the range of velocities allowed by ASHRAE 93-77.

The influence of wind velocity on the efficiency of unglazed collectors is even greater than indicated by Figure 3.5.1. ASHRAE Standard 96-80, "Method of Testing to Determine the Thermal Performance of Unglazed Flat-Plate Liquid-Type Solar Collectors" allows wind velocities only up to 1.3 m/s (3.0 m.p.h.) (Designers should beware of comparing 96-80 and 93-77 data, since the standards differ in several respects. The CSA standard on solar collectors, F378 - M1979, covers both types of collectors.)

A new revision of ASHRAE Standard 93 is now in progress. The committee recognizes that the wind velocity variation permitted is perhaps the greatest contributor to variations in the reported results. The new standard will probably require a narrower range of wind velocities during

testing, as well as improved measuring techniques. It will also probably specify a velocity of 4±0.5 m/s as the wind velocity for indoor testing.

Until these improvements in testing procedure are implemented, it is difficult for the designer to deal with the problem. Unless the wind velocity at which a test measurement was made is known, it is not possible to correct the results of the wind velocity at which efficiency calculations are required. All that can be done is to recognize that:

1. solar collectors will perform better in regions of low wind then regions of high wind, and
2. variations in wind velocity have induced considerable variation into the reported results of ASHRAE 93-77 collector tests.

The latter point does not suggest that collector efficiency results should be ignored.

Where data on wind velocity during a test is available, the best heat transfer correlation for correcting it is

$$Nu = .86\ R_e^{1/2}\ P_R^{1/3} \ *$$

where $Nu = hD_h/k$ (the Nusselt Number)

$R_e = VD_h\rho/M$ (the Reynolds Number)

$P_r = M/p\alpha$ (the Prandtl Number)

D_h = 4 x plate area/plate perimeter

h = heat transfer coefficient

k = thermal conductivity

---

* E.M. Sparrow, J.W. Ramsay and E.A. Mass, JGT, 101, 2, 1979, "Effect of Finite Width on Heat Transfer and Fluid Flow About an Inclined Rectangular Plate".

ρ = density

M = viscosity

α = thermal diffusivity

This equation agrees well with theory, and in particular it shows the correct variation of heat transfer with plate size, and the correct variation of heat transfer with the square root of velocity. It was obtained over the Reynolds Number range from 2×10^4 to 9×10^4, but it should be valid over the entire laminar flow range, up to a Reynolds Number of 10^6.

Where collectors are in a turbulent boundary layer, or in the wake of an object, the heat transfer prediction of the above equation should be increased by about 25%.

Solar energy textbooks often recommend an equation of the form $h = a + bV$ for the heat transfer coefficient. This formula ignores the effect of collector plate size, and incorrectly assumes a linear variation with velocity.

Some designers have the mistaken impression that sheltering a surface, such as a solar collector, from the prevailing wind behind some object will decrease the heat loss. This may occur at very low wind velocities; at higher velocities the eddies shed by the object may increase heat transfer. The same is true when the wind is from the back of the collector. At Reynolds numbers over 60,000 the heat transfer on the front surface will be greater than it would have been if the wind had been directly onto the front.*

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* E.M. Sparrow, ASHRAE Journal, July, 1982, "Wind-Related Heat Transfer Coefficients for Leeward-Facing Solar Collectors".

When the wind is very low, free convection will predominate. A good approximation for the free convective heat transfer coefficient is

$h = 4 W/m^2 \ ^\circ C$

at a surface-to-air temperature difference of 10°C. This value will vary with the cube root of the temperature difference.

Simplified solar energy system performance analysis methods such as FCHART do not take wind variations into account, although it is not difficult to do so with the hour-by-hour simulation procedures such as TRNSYS. The designer who is working in a climate having unusually high or low winds should make an estimate of the impact of this factor on system performance, using a calculation method with an accuracy level suited to the requirements of the particular job.

3.7 THERMODYNAMIC FACTORS

The standard approach to the analysis of the performance of thermal systems is to introduce the concept of the thermodynamically ideal system (for example, the Rankine cycle thermal power plant). This system operates reversibly, and thus its operation results in no increase of the entropy of the universe. This concept provides a performance standard for the equivalent real thermal system, and provides the designer with insights into how the system should be modified to make its performance closer to the ideal.

It is of little value to apply this concept to solar collectors. An ideal collector would have $F_R(\alpha\tau) = 1$ and $F_R U_L = 0$, but these goals are already obvious to the collector designer, and are also obviously not achievable or even approachable. A collector is a heat transfer device

and, like other heat transfer devices such as heat exchangers, it is by definition an entropy producer. The Second Law of Thermodynamics provides little insight into the performance of this kind of equipment.

Second Law analysis is valuable in analysing the performance of the remainder of the system. The ideal solar energy system is one which produces no entropy (outside of that necessarily produced by losses from the collector). Thus, it will have perfect insulation and, more important, it will have no mixing of fluid streams at different temperatures.

To achieve the latter requirement means that there must be no disturbance of the stratification of the storage tank; that the fluid entering the storage tank from the collector must do so at the point where the temperature of the stored fluid equals that of the entering fluid; and that the fluid entering the collector from the storage tank must do so at the point where the make-up fluid has reached the temperature in the bottom of the tank. Thus the ideal solar service water heating system has the configuration shown in Figure 3.6.1, with points A and B as movable injection points.

Of course, such a system cannot be built, but certain approximations to it can be made. For example, where water usage is steady, the two heat exchanger systems shown in Figure 3.6.2 can approximate the injection of water into the collector at the point where the temperatures are equal. This approach has been found to be cost effective in certain circumstances.

The two-tank two-valve system shown in Figure 3.6.3 is an approximation to injection into the storage tank at the point of equal temperatures.

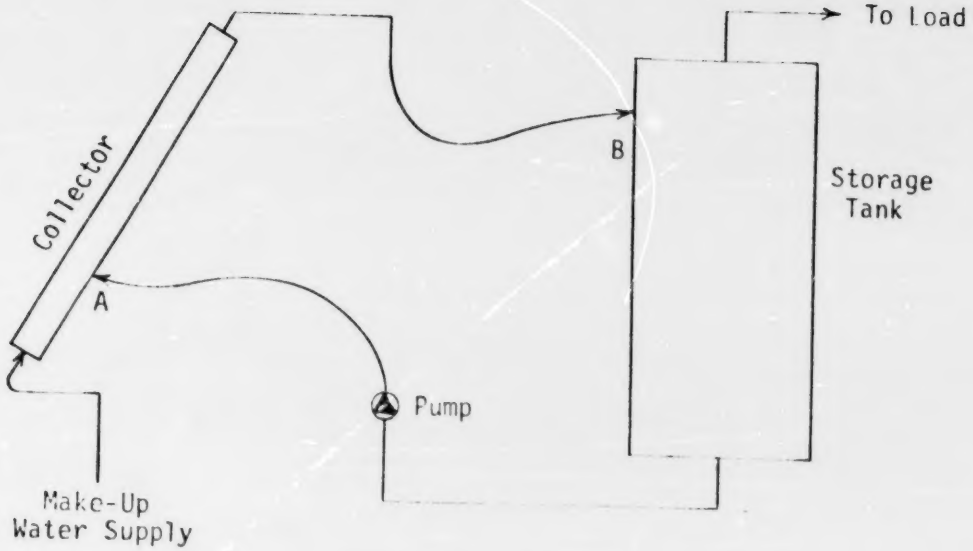

FIGURE 3.6.1

THERMODYNAMICALLY IDEAL SOLAR

SERVICE WATER SYSTEM

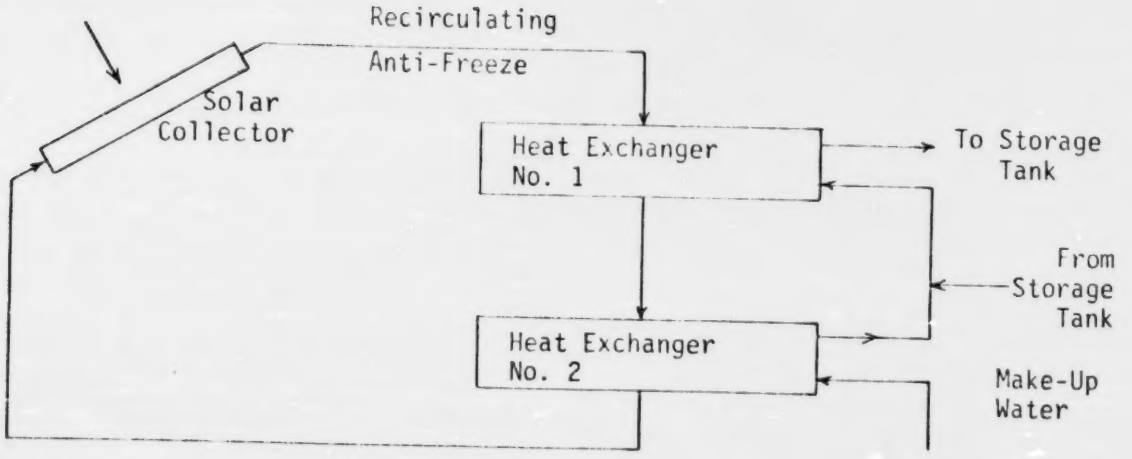

FIGURE 3.6.2

TWO HEAT EXCHANGER SYSTEM

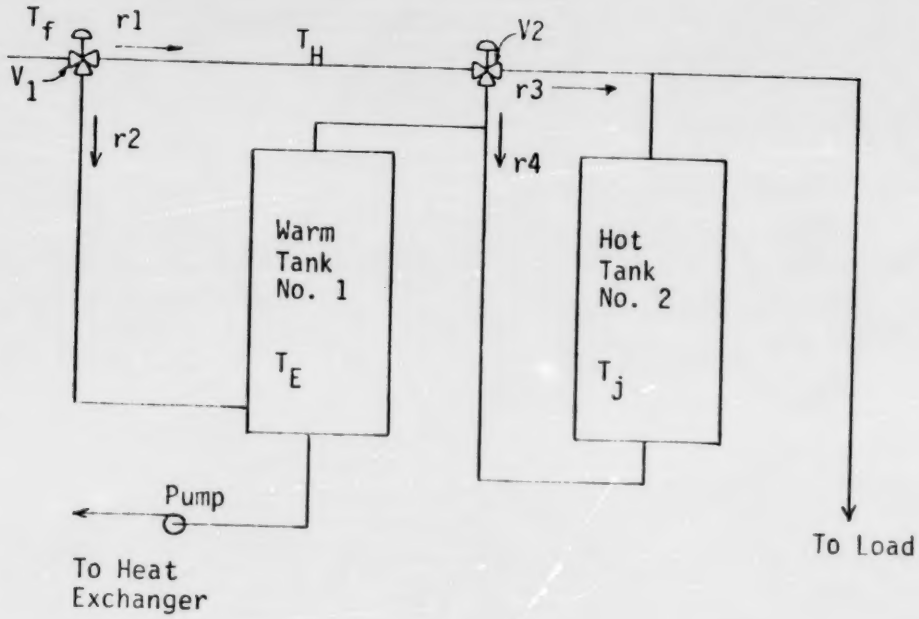

FIGURE 3.6.3

TWO VALVE TWO TANK SYSTEM

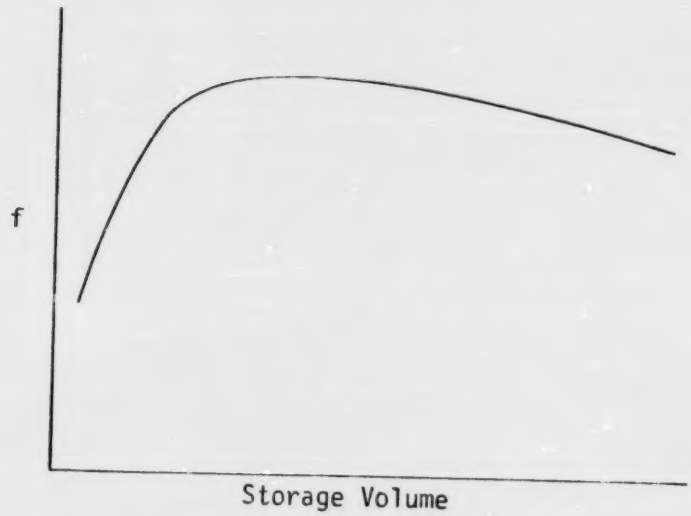

FIGURE 3.6.4

SOLAR FRACTION vs STORAGE VOLUME

FOR A SOLAR DHW SYSTEM

If $T_f < T_E$, then valve V_1 diverts the warm fluid along path r_2, and it recirculates without disturbing the tanks. Any water used will be drawn from the top of Tank 2 and made up at the bottom of Tank 1. If $T_f > T_E$, valve V_1 sends the fluid along path r_1 to valve V_2. If $T_H < T_J$, valve V_2 diverts the flow to path r_4 and the water recirculates through Tank 1, warming it up. Tank 2 is left undisturbed except that any water used will be drawn out of the recirculating loop, into the bottom of Tank 2 and out the top, thus sending the hottest water to the load. If $T_H > T_J$, the valve V_2 diverts water to path r_3 and recirculation is through both tanks, warming them up. Any water used is drawn from the recirculating loop before it enters Tank 2.

This scheme has been found to be cost effective in certain circumstances. Computer analysis indicates that it can more than double the solar fraction compared to the same system without the extra valves and controls. This concept can be extended to larger numbers of tanks and valves for larger systems where it can be shown to be cost effective.

In general, the thermal performance of a system will be enhanced by any factor that results in a lower collector inlet temperature (without wasting heat, of course). One such factor is a low supply water temperature. All other things being equal, a service water system supplied from a well will be a better application than the equivalent system supplied from the mains, in most locations in Canada. Another way of lowering inlet temperature is to combine two different loads in a single solar energy system. For example, a make up air preheater can further cool

the collector heat transfer fluid after it has passed through a heat exchanger where it has transferred heat to service water.

Another significant thermal performance factor is optimum storage capacity. In space heating applications an increase in storage capacity will always increase the thermal performance, although not necessarily in a cost-effective way, but in a solar service water heating system there is an optimum tank size above which thermal performance decreases. This optimum size is approximately equal to one day's water usage. The reason there is an optimum is that the only way energy can be withdrawn from storage in a service water heating system is by using water. Thus, if 500 L are to be withdrawn and the required temperature is 50°C, more energy will be gained from a 500 L tank of water at 45°C than from a 5000 L tank at 40°C, even though the 5000 L tank contains far more energy. This reasoning is independent of the fact that a larger tank with the same thickness of insulation will also lose more energy.

Figure 3.6.4 shows a typical variation of solar fraction versus storage volume for a solar service water heating system. Note that it is less dangerous to install too large a tank than too small, if the optimum size is not known exactly.

Choosing the right collector for the job is an important element in the production of a thermally efficient design. Section 3.2 discusses the importance of selecting a collector that performs well in the particular range of the parameter $(T_{f,i} - T_a)/G_T$ which it will experience. An unglazed plastic collector may perform better than an evacuated tube

collector for preheating well water in the summer (as well as being cheaper).

A frequently-tried concept in solar energy systems is the variation of flow rate through the collectors. Under certain circumstances this concept could improve system thermal performance if properly applied. In general, however, it is an erroneous idea. The fluid leaves the collectors at higher temperature, but the value of F_R is degraded and the collector efficiency is decreased; thus energy delivered is lowered.

The final topic to be mentioned in this section is controls. Solar heating systems only collect energy when they are operating, so the designer must ensure that a system is running whenever there is energy to be collected. This is not easy. Care must be taken to ensure that the system does not run when it would lose energy, and that it does not cycle on and off at high frequency.

3.8 ECONOMICS

This section covers the materials presented in Chapter 11 of Duffie and Beckman. However, the approach taken is that of "Design of Thermal Systems" by W.F. Stoecker, McGraw-Hill, 1971.

The basic problem of solar energy economics, like that of the design of any other system where capital investments made now can reduce future running costs, is to compare expenditures and incomes made at different times. This is particularly true in an inflationary economy.

To find the present value of a payment made n years in the future, the amount of the payment is multiplied by the present worth factor,

$$P.W.F. = \frac{1}{(1+y)^n} \qquad \text{(Eqn. 3.7.1)}$$

where y is the interest rate. Similarly, dividing an investment made today by the PWF will predict its value n years in the future.

If a series of annual payments are to be made over the next n years, the present value can be found by multiplying the annual payment by the series present worth factor,

$$SPWF = \frac{1 - (1+y)^{-n}}{y} \qquad \text{(Eqn. 3.7.2)}$$

Similarly, dividing a debt incurred today by the SPWF will determine the annual payments necessary to pay it off in n years.

If it is required to calculate the present value of a fuel saving worth $1.00 this year that will continue for n years, inflation as well as interest must be taken into account. This can be done by defining y as the effective interest rate

$$y = \frac{i - x}{I + x} \qquad \text{(Eqn. 3.7.3)}$$

where i is the nominal interest rate and x is the inflation rate for the commodity in question (in this case, fuel). This expression, and the equations for PWF and SPWF are valid for $n>i$ and for $n<i$, but if $y=0$ the SPWF equation must be replaced by $SPWF=n$.

Example

A solar energy system costing $100,000 is projected to last 20 years and require major maintenance after 10 years. This major maintenance would cost $10,000 today and its cost is escalating at 6%. The annual maintenance cost is $500, escalating at 6%. The system saves $6870 per

year of oil, escalating at 8%. The discount rate is 10%. Is this a good investment.

Present values:

1. Major maintenance

$$P.V._{mm} = 10000 \times PWF_{mm}$$

$$Y_{mm} = \frac{i - x}{I + x} = \frac{.1 - .06}{1.06} = .0377$$

$$PWF_{mm} = \frac{1}{(1+y)^n} = \frac{1}{(1.0377)^{10}} = .6907$$

$$\therefore P.V._{mm} = 10{,}000 \times .6907 = \$6907.$$

2. Minor maintenance

$$P.V._{a.m.} = \$500 \times SPWF$$

$$y_{a.m.} = .0377$$

$$\therefore SPWF_{a.m.} = \frac{1 - (1+y)^{-n}}{y}$$

$$= \frac{1 - (1.0377)^{-20}}{.0377}$$

$$= 13.8714$$

$$\therefore P.V._{a.m.} = \$500 \times 13.8714$$

$$= \$6936$$

$$\therefore P.V._{costs} = 100{,}000 + 6907 + 6936$$

$$= \$113{,}843$$

3. Fuel Savings

$$P.V._{f.s.} = 6870 \times SPWF$$

$$Y_{f.s.} = \frac{.1 - .08}{1.08} = .0185$$

$$\therefore SPWF_{f.s.} = \frac{1 - (1.0185)^{-20}}{.0185}$$

$$= 16.5876$$

$$\therefore P.V._{f.s.} = \$6870 \times 16.5876$$

$$= \$113,957$$

$\therefore P.V._{f.s.} > P.V._{costs}$ and the system is a good investment.

Assignment

Oil costs 12¢/L (39000 kJ/L) and is escalating at 14%/year. A solar service water heating system will produce 1000 MJ/day of heat. It costs $100/year to maintain (escalating at 8%). The salvage value of the solar energy system will be $1000 in 20 years. (In making this estimate, inflation has been taken into account, so this figure is in year 2001 dollars, not year 1981 dollars.) The efficiency of the backup oil burning system is 60%. The interest rate is 11%. How much can you pay for the solar energy system?

Figure 3.7.1 shows a typical economic optimization plot. Summing the present value of future fuel expenditures and the system capital cost produces a curve which has a minimum at a particular collector area. The value is below the present value of fuel expenditures without a solar energy system, so the collector area at the minimum is obviously the correct amount to install.

Another possible economic optimization curve is shown in Figure 3.7.2. In this case, even the optimum solar energy system size results in a greater present value of total costs than no solar energy system. If there are non-economic motives for building a solar energy system, the optimum point still provides guidance as to the best system size. However, when

the (positive) slope of the solar energy system capital cost curve is always greater than (negative) slope of the present value of fuel costs curve, there will be no optimum. In this case the designer who has reasons other than economic ones for building a solar system will also have to use a non-economic approach to determining system size.

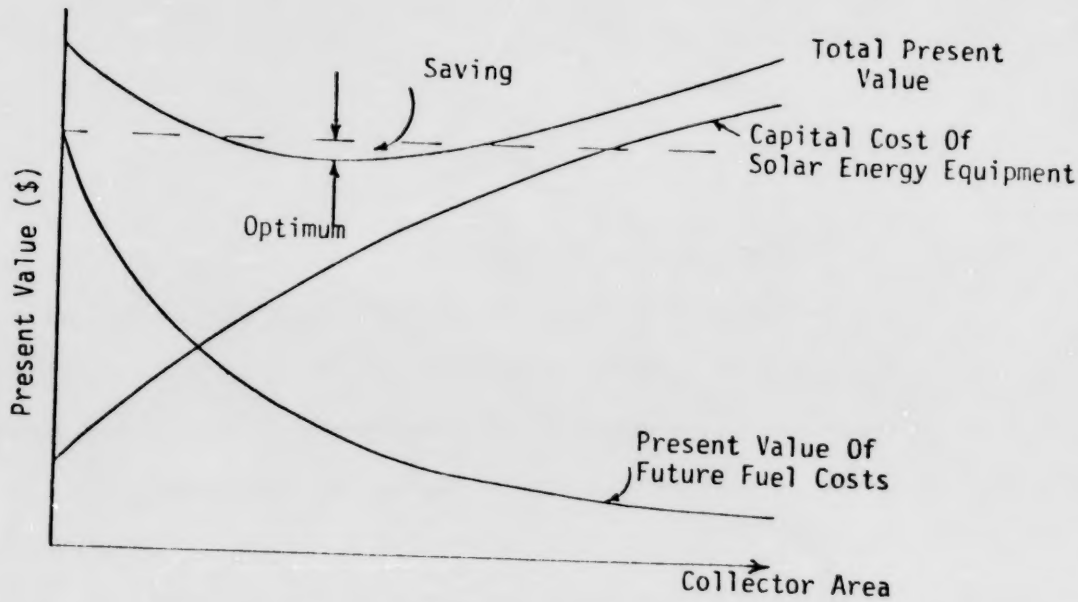

FIGURE 3.7.1

ECONOMIC OPTIMIZATION

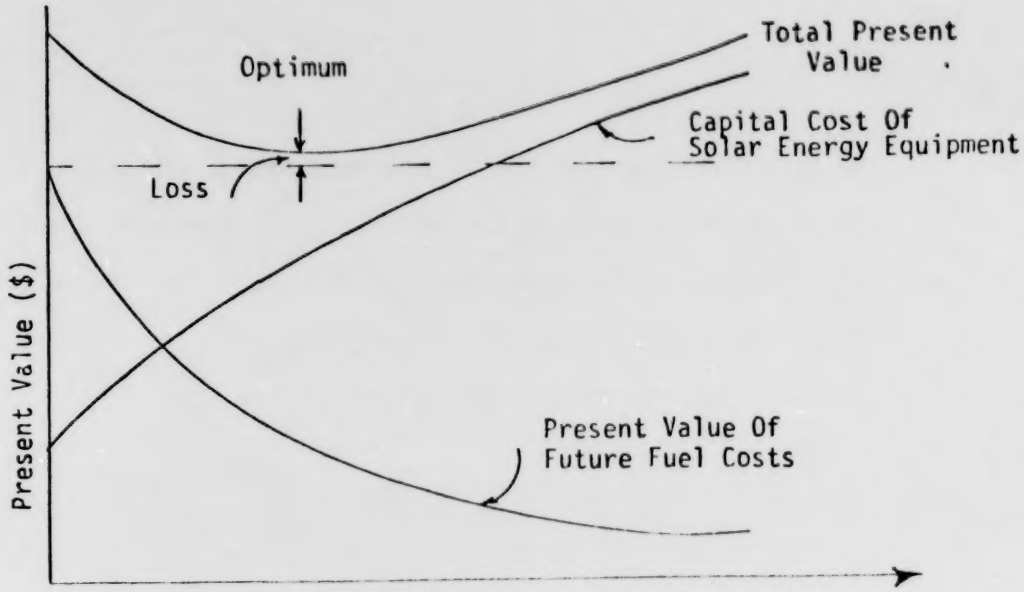

FIGURE 3.7.2

ECONOMIC OPTIMIZATION

3.9 SYNTHESIZING THERMAL AND ECONOMIC FACTORS INTO A SYSTEM DESIGN

A designer who wished to develop an optimized solar energy system would require a fairly complex computer program to do so. First, a precise thermal model is needed to distinguish the effects of the variables to be optimized (for example, the effect of an extra temperature controlled diverting valve in a multi-tank storage system). This program would then be built into an optimization program using one of the several optimization techniques available (See Stoecker, Page 108), and the program supplied with the costs of all the possible components. This approach is widely used in the design of thermal storage. For example, a refrigeration equipment manufacturer will use this approach in selecting the components of a heat pump.

The problem with applying this approach to solar energy system design is that design costs are part of the optimization equation. Larger solar energy systems are unique designs and only a limited effort can be spent on optimizing them before the design costs begin to outweigh the system cost savings. Even solar domestic water heating systems are not sold in large enough volumes to justify major expenditures on optimization.

Lacking the opportunity to do detailed analysis of cost-effectiveness, the solar energy system designer must rely on judgment, experience, and rules-of-thumb to produce the most economic systems possible. Many factors that make systems more economic are related to the site, so that good design becomes more a question of recognizing good applications and good sites than one of fitting systems to pre-determined sites. Among the important factors to look for in a site are:

a) an existing roof or other structure with the right slope and orientation, to save the cost of a support system;

b) sufficient space for the mechanical equipment, close to the collector array, and with easy accessibility;

c) a load that is close to the room where the solar energy system will be installed;

d) no shading from adjacent structures, and a low probability of future construction;

e) a site and a load with projected lifetimes greater than the projected solar energy system lifetime;

f) a low probability of vandalism;

g) the availability of maintenance staff; and

h) sub-metering on the load to be met, so that system sizing is easier and future monitoring of performance will be cheaper.

Among the important factors to look for in the load itself are:

a) a low temperature load (note the preheating boiler feed water can be a low temperature load. The required temperature is less important then the inlet temperature).

b) a large load, which permits economies of scale and also permits keeping the mean system temperature low,

c) a good time variation of the load. (The best time variation would be one that follows the availability of sunlight both through the day and through the year. The worst would be one that was concentrated in the winter and at night, such as a space heating load) and

d) a load that is being met by a high priced fuel and for which no cheaper alternatives are readily available.

Given a good site and a good load, it remains to the designer to apply the principles of good thermal performance outlined in Section 3.6 above, and to design the cheapest possible system consistent with meeting the design objectives outlined in Section 3.2. There are two final principles which the designer should keep in mind. One is that a high solar fraction is not related to cost effectiveness. It may well be worthwhile, for example, to abandon the winter portion of a service water heating load to the electrical backup system, and avoid the cost of a separate heat transfer loop with freeze protection. The second point is that the PUSH Program has as its objective the development of a solar equipment manufacturing industry, not a plumbing hardware industry, so that trade-offs between equipment investments should be slanted towards the collectors rather than the associated equipment.

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CHAPTER 4

SIMULATION TECHNIQUES

Several computer programs are available to assist in the analysis and design of solar energy systems. Two of the most widely used programs are FCHART and TRNSYS. FCHART is based on a correlation of the results of hour by hour annual TRNSYS simulations. Other frequently used programs are WATSUN, DOE-2, BLAST, ENERPUB, VENTAIR and ASTEPI.

4.1 THE TRNSYS COMPUTER PROGRAM

TRNSYS is a transient system simulation program, which was developed at the University of Wisconsin Solar Energy Laboratory. TRNSYS was then used to develop the FCHART program, which is not as versatile as TRNSYS but is much easier to learn and use. FCHART is used for the analysis and design of active solar and heat pump heating systems. It is a self-explaining interactive program which allows the user to quickly describe the system and which provides a straightforward table of results.

By comparison, TRNSYS requires some knowledge of computer programming. TRNSYS is capable of simulating almost any solar thermal energy system. A system is described by a set of components which are interconnected. The programmer specifies which components are included in the system and the manner in which they are interconnected. Most systems described in this manner can be simulated using components found in the TRNSYS library. However, other components may also be modelled by writing Fortran subroutines to simulate the desired components. The TRNSYS library includes

the following component models: data reader; solar radiation data processor; shading algorithm; flat plate collector; CPC collector; mass wall; direct gain window; pipe and duct; pump/fan; flow diverter/mixing valve/tee piece; controller with hysteris; three-stage thermostat; relief valve; heat exchanger; storage tank; rock bed; heat pump; absorption air conditioner; auxilliary heater; liquid collector-storage subsystem; air collector-storage subsystem; domestic hot water subsystem; energy (degree-hour) space heating or cooling load; cyclic time-dependent function generator; algebraic operations unit; quantity integrator; printer; plotter; time and frequency distribution plotters; simulation summarizer and wall; roof-and-attic, room and basement-transfer function models.

The TRNSYS program also requires that the programmer select the format and contents of the output, while FCHART is programmed to provide a monthly breakdown of annual system performances. However, TRNSYS is capable of simulating the system for any desired period using any chosen timestep. For example, the system can be simulated hourly for a day, daily for a month, weekly for a year, etc.

4.1.1 Advantages of TRNSYS

1. The programmer is able to select the content and the format of the TRNSYS simulation output.
2. The programmer is able to select the timestep and the length of the simulation used by TRNSYS.
3. TRNSYS's modular system provides a tool for easy simulation. The entire problem of system simulation reduces to a problem of identifying all components and formulating a general mathematical description of each.

4. In TRNSYS's modular system, many components are common to different systems and can thus be used in these systems with little or no modification.

5. Transient systems can be simulated by TRNSYS in great detail.

4.1.2 Disadvantages of TRNSYS

1. Learing the TRNSYS program is a long process, and may require a learning period five to ten times greater than FCHART.

2. Running the TRNSYS program is very expensive compared to other available programs which may be used, such as FCHART. For example, comparable annual simulations of a solar DHW system typically cost over $30 using TRNSYS and less than $1.00 using FCHART. Research of the University of Wisconsin Solar Energy Laboratory indicates a very close correlation between FCHART and TRNSYS - usually within a few percent.

3. TRNSYS component models or subroutines not in the library are difficult to program, and require relatively large amounts of computer time. The compact subsystems found in the TRNSYS library are most efficient and therefore use less computer time. The solar DHW system referred to above was based on the TRNSYS solar DHW subsystem. The system was rerun using separate storage tank and auxiliary heater subroutines, and the cost was just over $50.

4.2 THE FCHART COMPUTER PROGRAM

This computer simulation program is the correlation of the results of many hundreds of thermal performance simulations using the TRNSYS program. These simulations were performed for a range of parameters which are found in practical system designs. The most important design parameter is collector area. Other variable parameters include collector type, storage

TABLE 4.2.1

RANGES OF DESIGN PARAMETERS
USED IN DEVELOPING FCHART

$0.6 \leq (\tau\alpha)_n \leq 0.9$

$5 \leq F'_R A \leq 120\ m^2$

$2.1 \leq U_L \leq 8.3\ W/m^2C$

$30 \leq \beta \leq 90$ deg.

$83 \leq (UA)_h \leq 667\ W/m^2C$

capacity, fluid flow rates, and load and collector heat exchanger sizes. Ranges of the design parameters used in developing FCHART are shown in Table 4.2.1.

The FCHART simulation program incorporates three basic system configurations - liquid and air systems for space and hot water heating and systems for service water heating only. FCHART calculates the monthly system performance from long term averages of monthly meteorological data and the input parameters.

FCHART is based on the following assumptions:

1. All liquid storage tanks are assumed to be fully mixed.
2. The hot water demand in a DHW system is assumed to be the daily mass flow profile developed by a Rand Corporation survey normalized and applied for a user-specified daily mass demand (see Figure 4.2.1).
3. The solar collectors are assumed to have a straight line efficiency curve.
4. The solar radiation is considered to be symmetrical about solar noon.
5. The systems are well designed and well-built, the flow distribution is uniform, the flow rate corresponds to the collector performance data used and the systems are similar to the computer models.

4.2.1 FCHART Utilizability

Utilizability is defined as the fraction of the incident solar radiation that can be converted to useful heat by a collector with $F_R \tau\alpha = 0.9$ and a fixed inlet to ambient temperature difference. FCHART uses the monthly average utilizability as a parameter in the design of liquid systems for space heating and combined space and water heating.

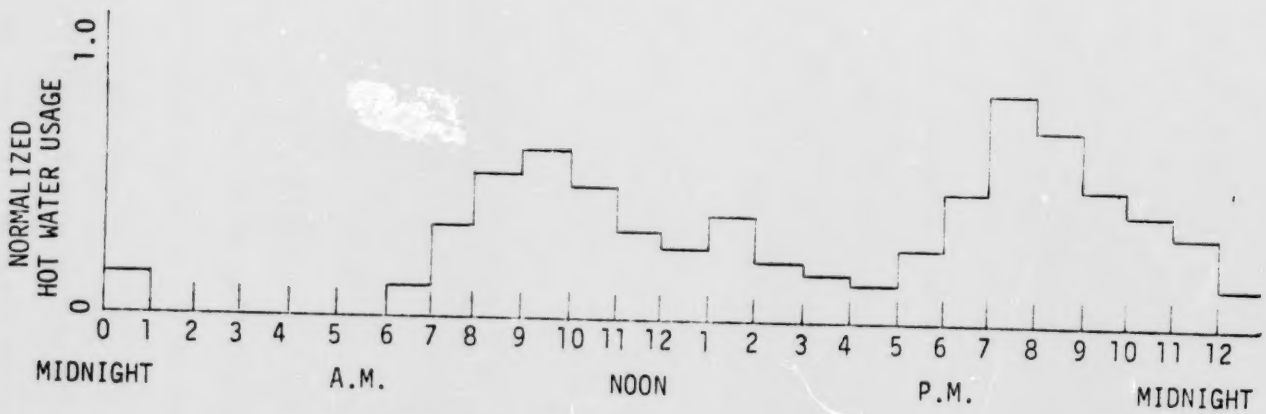


FIGURE 4.2.1 Daily Mass Flowrate Profile

The following two correlations for utilizability are used in FCHART. For flat plate collectors, utilizability is defined as the fraction of radiation, above a fixed critical level, which is incident upon a collector surface. This critical level is found by setting the collector useful output (Q_u) equal to zero in the following equation,

$Q_u = A_c F_R [I_t (\tau\alpha) - U_L (T_i - T_a)]$. For concentrating collectors, utilizability is defined as the fraction of radiation, above the fixed critical level, which is incident upon a collector surface over the period of time that the collector operates.

4.2.2 FCHART Output Analysis

The FCHART computer simulation output consists of an evaluation of the system thermal performance, a summary of the purchased energy and, optionally, a life cycle analysis. These results depend on the type of system chosen, the options selected and the parameter values which were used. Once the proposed system has been designed and the input parameters have been chosen, the system may be simulated.

The monthly system performance is evaluated using the equipment characteristics which were input and the long-term average of recorded weather data. FCHART is a very good tool for the long-term prediction of solar energy system performance.

The economic analysis of a design may be hand calculated, or obtained from the FCHART output. Use of the FCHART economic analysis will depend on the needs of the user. If a simple payback period is sufficient, the FCHART economic analysis need not be simulated. However, if a more in

depth analysis is required, including corrections for depreciation, interest and inflation, the FCHART simulation should be used.

The FCHART life cycle cost analysis output has three levels of detail which may be selected according to the user's requirements. FCHART also has the capability to compare the life cycle costs of two systems. This comparison may be obtained in two degrees of detail. A detailed explanation of the economic analysis may be found in the user's manual.

4.3 THE WATSUN COMPUTER PROGRAM

WATSUN is a series of generalized computer programs developed at the University of Waterloo as a design aid for the study of solar-assisted domestic hot water and space heating systems. WATSUN uses many of the algorithms used in the TRNSYS and FCHART computer programs. Like FCHART, WATSUN uses total system configurations rather than the TRNSYS-type component models. WATSUN uses actual weather data to simulate the hour-by-hour operation of the system. Like TRNSYS, the starting day, length of simulation period and output timestep are specified by the WATSUN user. However, certain assumptions in WATSUN can make the validity of short-term simulations (less than a few weeks) questionable. In addition, the economic analysis uses a one year base to project the economic performance of the system over its lifetime. Thus, the economic analysis is produced only for simulations that are exactly one year in length.

WATSUN requires slightly more detailed input than FCHART. WATSUN has the capability to alter the hourly and daily domestic hot water load profiles. WATSUN also has the capacity to simulate identical systems with

incremental changes in a variable. WATSUN will simulate the system operation for a given collector area and storage-volume to collector-area ratio. If specified, the collector area is then increased (the storage volume to collector-area ratio remains constant) and the simulation is repeated. This cycle continues until the maximum collector area is simulated. The collector area is then reset to its initial value and the cycle is performed for incremental changes in the storage-volume to collector-area ratio. The cycle ends when the combination of the maximum area and the maximum volume to area ratio has been simulated.

4.4 THE ENERPUB COMPUTER PROGRAM

The ENERPUB computer program, developed by Enermodal Engineering Limited for Public Works Canada, can be used to simulate the performance of liquid-based seasonal or short-term storage solar space heating systems with or without a heat pump. The program can also simulate the performance of a solar heating system used to heat oil in oil storage tank. ENERPUB is not suitable for simulation of solar domestic hot water systems specifically because of the restrictive heat exchanger models.

The ENERPUB program has many advantages over other solar simulation programs. Because performance calculations are made for each simulated hour, the program results are potentially more accurate than those of programs using a monthly calculation procedure, such as FCHART. In addition, the ENERPUB program can simulate a wider range of parameters than programs restricted by monthly average correlation equations. Several of the models in the ENERPUB were adapted from WATSUN models (WATSUN is an

hour-by-hour computer program developed by the University of Waterloo). ENERPUB has several enhancements over the WATSUN space heating programs:

1) Stratified tank model for short term or seasonal storage.

2) Four possible heat pump locations.

3) Inclusion of heat loss from the storage to the building, outdoors or ground.

4) Inclusion of heat loss from collector and storage piping to the building, outdoors or ground.

The ENERPUB computer program gives detailed and accurate results for liquid-based seasonal or short-term storage provided that reasonable values for all system parameters are input. All users should read and understand this manual before using the program.

4.5 THE VENTAIR-2 COMPUTER PROGRAM

The VENTAIR-2 computer program was developed by Enermodel Engineering Limited for Public Works to simulate the performance of air-based solar collectors used in the preheating of industrial process or building ventilation air. The program can accept data of all PUSH approved air-based collectors (Amherst 200, Solartech Solair, and Watershed A100) and any other parallel plate air-based collector.

VENTAIR-2 is the only computer program capable of simulating solar preheating of process or ventilation air. Performance calculations use a one-hour time step to ensure maximum accuracy. An important restriction, however, on the use of the program is that the air demand must be constant over the hour. A system not applicable to the VENTAIR-2 program, for

example, is a bathroom ventilation system operating by a light switch or short duration timer.

The VENTAIR-2 computer program will provide an accurate estimate of thermal performance of solar preheated process or ventilation air systems provided that the user supplies system parameters within the program limitations.

In many buildings a high rate of change of ventilation air is necessary for the health of the occupants or proper operating of equipment. Such buildings include hospitals, vehicle maintenance garages, indoor swimming pools and commercial kitchens. The volumes of air involved are often quite large (6 air changes/hour) and correspondingly large quantities of energy are required to raise the air temperature to the building temperature. This air is normally heated by steam coils or electric resistance heaters.

To reduce energy consumption, heat recovery equipment can be used to transfer some of the heat from the exhaust air to the fresh air. Heat recovery equipment, however, has several limitations. This equipment suffers from frost build-up in sub-freezing conditions, fouling from kitchen grease, and requires modifications if the exhaust air contains toxic chemicals. The installation of this equipment can be expensive in retrofit situations if return air duct work must be added.

Use of air-based solar collectors to preheat ventilation air has been proposed as a parallel application of a viable alternative to heat recovery equipment in many applications. In making a decision to use this type of system, it is necessary to estimate the yearly thermal performance. The

VENTAIR-2 computer program was designed specifically to assist the designer in evaluating the system performance of solar preheated ventilation air systems.

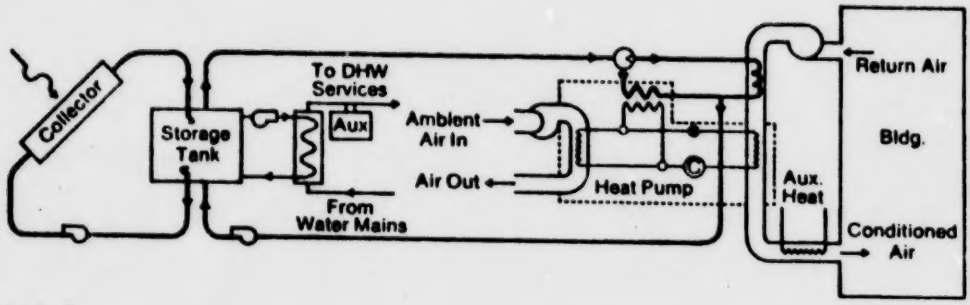
Many industrial processes require large volumes of air for drying and/or heating. Such processes include paint drying, food drying, combustion air preheating and sterilization/drying of bottles and cans. The VENTAIR-2 computer program can also be used to simulate solar preheating of these processes provided that the air flow is constant over each hour. If the flow rate is dependent on the relative humidity and/or ambient temperature the VENTAIR-2 computer program is not suitable.

4.6 ASTEPI

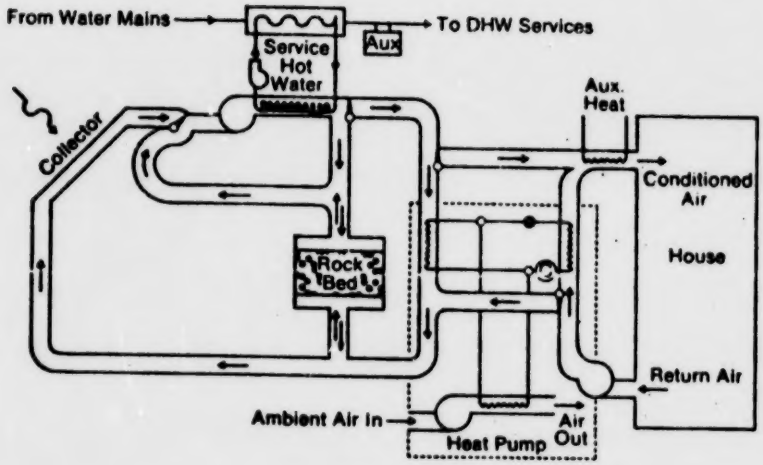
ATTEPI (Annual Storage solar Energy Program) is a computer program written in PL/1, at the University of Toronto designed to simulate the hourly performance of solar heating systems for space and service water heating. Although emphasis is directed to seasonal storage systems, options are included to permit the simulation of short term storage systems as well as a combined seasonal storage and short term storage system.

ASTEPI is designed to utilize the newly expanded solar radiation data base of the Canadian Atmospheric Environmental Service (AES).

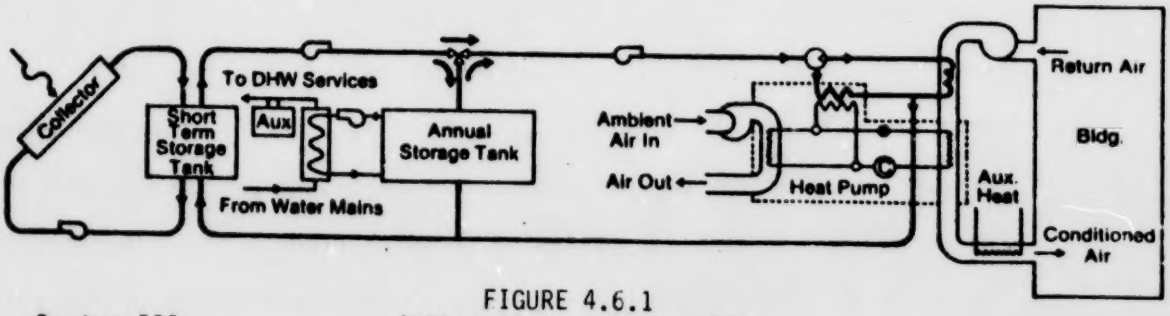
The simulation proceeds in an hourly stepwise fashion, assuming in any given hour that the weather inputs (outside dry bulb temperature and solar irradiance) and other system parameters (i.e. hot water storage temperature, building energy demand) are constant. This reduces the time dependent differential equations associated with the thermal performance of the



System I



System II



System III

FIGURE 4.6.1
ASTEPI BASIC SYSTEM TYPES

system to the simpler algebraic equations which can be solved directly. Although the large thermal storage tanks associated with annual storage undergo little temperature change on a daily basis, let alone hourly, there is advantage in calculating hourly instead of daily. This is due to an increased accuracy in the collected solar energy calculation. Experimental collector performance data (slope, intercept of efficiency curve) based on the collector inlet fluid temperature are used to model the collector performance.

Storage heat loss data, based on detailed conductive soil heat transfer calculations for buried right bylindrical tanks, are used as input to a lumped parameter effective thermal resistance (ETR) model for estimating tank heat losses.

ASTEPI is designed to simulate a number of cases in a single run, allowing the operator to examine the effects of changing one or more parameters.

4.7 THE BLAST COMPUTER PROGRAM

The Building Loads Analysis and System Thermodyamics (BLAST) program was developed by the U.S. Army Construction Engineering Research Laboratory under the sponsorship of the Air Force Engineering and Services Center, Tyndall Air Force Base, Fl. and the Department of the Army, Office of the Chief of Engineers, Washington, D.C. BLAST is a set of subprograms used for predicting energy consumption and energy system performance and cost in buildings. BLAST is a very detailed computer program that simulates hour by hour space heating and cooling loads, hourly performance of fan systems,

hourly conventional heating and cooling plants, total energy plants and solar energy systems, and life cycle costs.

BLAST may be used for both new and existing buildings. During the preliminary design phase of a new building it may be used to perform cost-benefit analyses of design options such as site location and building orientation, size, shape and fenestration. It can also be used to determine the best operating strategies and to size the HVAC equipment. In existing buildings BLAST can be used to determine changes in operating strategies.

BLAST is able to simulate solar collectors as well as such passive solar energy system details as Trombe Walls and movable insulation. While BLAST is not normally used to simulate the performance of a solar energy system, it is used to compare the performance of a solar energy system to that of a conventional HVAC system. Details of the BLAST program may be found in the user's manual.